POPPING AND FLAKING QUALITY OF SORGHUM CULTIVARS IN RELATION TO PHYSICOCHEMICAL CHARACTERISTICS AND *in vitro* STARCH AND PROTEIN DIGESTIBILITY

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CERTIFICATE

MISS. Y.S. SAILAJA has satisfactorily prosecuted the course of research and that the thesis entitled **"POPPING AND FLAKING QUALITY OF SORGHUM CULTIVARS IN RELATION TO PHYSICOCHEMICAL CHARACTERISTICS AND *in vitro* STARCH AND PROTEIN DIGESTIBILITY"** submitted is the result of original research work and is of sufficiently high standard to warrant its presentation to the examination. I also certify that the thesis or part thereof has not been previously submitted by her for a degree of any University.

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CERTIFICATE

This is to certify that the thesis entitled **"POPPING AND FLAKING QUALITY OF SORGHUM CULTIVARS IN RELATION TO PHYSICOCHEMICAL CHARACTERISTICS AND *in vitro* STARCH AND PROTEIN DIGESTIBILITY"** submitted in partial fulfilment of the requirements for the degree of **"DOCTOR OF PHILOSOPHY IN HOME SCIENCE"** of the Andhra Pradesh Agricultural University, Hyderabad, is a record of the bonafide research work carried out by **MISS. Y.S. SAILAJA** under my guidance and supervision. The subject of the thesis has been approved by the Student's Advisory Committee.

No part of the thesis has been submitted for any other degree or diploma. The published part has been fully acknowledged. All assistance and help received during the course of the investigations have been duly acknowledged by the author of the thesis.

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DECLARATION

I, **Y. S. SAILAJA**, hereby declare that the thesis entitled "**POPPING AND FLAKING QUALITY OF SORGHUM CULTIVARS IN RELATION TO PHYSICOCHEMICAL CHARACTERISTICS AND *in vitro* STARCH AND PROTEIN DIGESTIBILITY**" submitted to Andhra Pradesh Agricultural University for the degree of Doctor of Philosophy in Home Science is the result of original research work done by me. I also declare that the material contained in the thesis has not been published earlier.

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ABSTRACT

Grain sorghum is an important staple food for more than 700 million people of the semi-arid tropics. In addition to the traditional uses, new methods of processing have to be developed for the increased utilisation of the grain. A number of processes are used in the preparation of ready-to-eat cereals including puffing, flaking and shredding of wheat, corn and rice but none for sorghum. Physical and chemical properties of grain affect the processing and food-making properties. On processing various physicochemical changes occur which are beneficial and also detrimental to the quality. The objective of this study was to develop/improve the sorghum popping and flaking processes and to study the popping and flaking quality of 20 sorghum cultivars in relation to their grain characteristics, *in vitro* starch and protein digestibility.

Wide variation among cultivars was observed in the physicochemical and starch properties of the grain. Popping and flaking methods were standardised using two cultivars. The grain samples were popped at 16% moisture level using corn popper. For flaking, the dehulled grains were soaked in water, pressure cooked, conditioned and flaked using flaking rolls.

There were significant genotypic differences among cultivars for popping and flaking quality. *In vitro* starch and protein digestibility of grain showed variation among the cultivars. Popping and flaking caused a shift in protein and starch digestibilities of the grain. A five- fold increase in starch digestibility was observed in both the processes. However, heat processing had a deleterious effect on protein digestibility which is more pronounced in flaked products.

Taste panel evaluation showed significant variation among cultivars for all the sensory qualities of pops. In flakes the color and appearance, and texture showed significant variation among cultivars. Physicochemical characters of grain such as bulk density, floaters percent, endosperm texture, amylose content showed strong association with the popping and flaking quality. Swelling power, solubility of starch, pasting temperature and viscosity of flour also showed significant relationship with the popping and flaking quality parameters.

INTRODUCTION

CHAPTER I

INTRODUCTION

Grain sorghum (*Sorghum bicolor* L. Moench) is a staple food in the semi-arid tropics. Asia and Africa contribute about 65 per cent of the total grain sorghum production in the semi-arid tropics. About 700 million people are nourished by sorghum, since it constitutes a source of calories, protein and minerals. Progress has been made in developing high yielding varieties and hybrids with improved agronomic traits, that resulted in excess production.

Sorghum produced in India is consumed mostly in the form of roti (unleavened bread) and sankati (thick porridge). Besides traditional uses, sorghum can also be used, alternatively, for popping and flaking. Apart from the use as snack food, popped sorghum can be used in weaning food formulations. Sorghum flakes will be a good alternative for corn flakes as breakfast cereal and as adjuncts in brewing industry. Utilization of sorghum in the form of ready-to-eat pops and flakes is likely to improve its consumption significantly.

A number of different processes are used in the preparation of ready-to-eat cereals, including flaking, puffing, shredding and granule formation in wheat, corn and rice. Whereas, sorghum flaking and popping processes have not been explored and very little information is available in the literature. Improved processing methods for popping and flaking have to be developed for the utilization of the increased grain sorghum production.

The grain characteristics required to produce traditional food products of high quality have been reported (Rooney and Murty, 1982; Rooney *et al.*, 1986). However, very little is known about the physicochemical characteristics of grain which influence the processing and sensory quality of sorghum pops and flakes so as to select appropriate cultivars for popping and flaking.

The effect of modern methods of processing of wheat on the *in vitro* starch digestibility has been investigated by earlier workers (Holm *et al.*, 1985 and Holm and Bjorck, 1988). Cooking has also been found to lower protein digestibility in sorghum (Axtell *et al.*, 1981). During processing, some interactions do occur among the constituents of grain. These interactions might lead to some changes that affect the digestibility of constituents and thereby its nutrient availability.

The present study was undertaken with the objective to standardize the popping and flaking processes. This also aimed to study the popping and flaking quality of sorghum cultivars in relation to their grain characteristics and *in vitro* starch and protein digestibility.

REVIEW OF LITERATURE

CHAPTER II

REVIEW OF LITERATURE

Information available in literature on the quality aspects of popping and flaking, *in vitro* starch and protein digestibility and the relationship of grain characteristics in sorghum and some of the other cereals is reviewed under the following headings.

- o Physical properties and chemical composition of grain
- o Physical properties of starch
- o Popping and flaking quality
- o Organoleptic evaluation and objective measurement of crispness of pops and flakes
- o Influence of processing on *in vitro* starch digestibility
- o Influence of processing on *in vitro* protein digestibility

2.1 PHYSICAL PROPERTIES OF GRAIN

Physical properties of grain vary considerably due to the influence of genotype and environment. The influence of certain physical characteristics of grain such as hardness or vitreousness on the quality of traditional sorghum food products has been well demonstrated (Murty and House, 1980; Rooney *et al.*, 1980, Cagampang *et al.*, 1982; Rooney and Murty, 1982). Sorghum grains with a high proportion of vitreous endosperm are preferred for making thick porridges, cookies and for popping (Chandrashekar and Desikachar, 1986;

of floury endosperm are preferred for making fermented and unfermented bread (Rooney *et al.*, 1986).

Studies made by Maxson *et al.* (1971) on milling quality of sorghum using barley pearler showed that the endosperm texture was related to milling quality and grain hardness. Viraktamath *et al.* (1972) reported the yield of the pearled product to vary from 83 to 97 per cent in 14 sorghum cultivars.

Kirleis and Crosby (1982) and Hallgren and Murty (1983) suggested the use of floatation technique for routine evaluation of grain hardness in quality breeding programs. The floaters per cent in their studies was correlated with percentage vitreousness, grain hardness (work required for grinding), breaking strength of individual kernels and flour particle size.

Murty *et al.* (1984) reported a strong association between endosperm texture, pearling quality and flour particle size measurements and concluded that these parameters could be used to evaluate grain hardness in sorghum. The per cent vitreousness (grain hardness) data of 15 sorghum cultivars were significantly related to adhesion value,cooked grain texture, alkali gel stiffness value, weight ratio of cooked to uncooked grain, and amylograph viscosities (Cagampang and Kirleis, 1984).

Stroshine *et al.* (1981), Paulsen *et al.* (1982) and Pomeranz *et al.* (1986) observed a negative correlation between test weight and per cent floaters in corn genotypes. Kirleis and Stroshine (1990) found that corn kernel density was the best single predictor of dry-milling quality. Wu and Bergquist (1991) reported a negative correlation between grain density and per cent moisture. Dorsey-Redding *et al.* (1991) observed significant correlations between hardness, test weight, and kernel density in corn genotypes.

2.2 CHEMICAL COMPOSITION

In general, the composition of sorghum is similar to that of maize with a few, but significant differences (Hulse *et al.*, 1980; Rooney *et al.*, 1980; Hoseney *et al.*, 1981). Chemical composition varies significantly due to genotype and environment. The variability is probably due to the fact that sorghum is produced under more variable conditions than most other cereals.

Miller and Burns (1970) reported the starch content of 17 varieties of grain sorghum to range between 64.2 and 70.6 per cent and that of amylose of total starch ranged between 0.79 and 34.8 per cent. They observed a direct relationship between amylose and starch content. Sullins and Rooney (1974) reported the starch content as 66.7-75.2 per cent and amylose content as 0.22-0.29 per cent on analysis of 4 sorghum lines.

According to Hulse *et al.* (1980) starch, cellulose, simple sugars and pentosans comprise approximately 80 per cent of the dry weight of the kernel with starch usually 70-75 per cent. Sorghum starch contains 20-30 per cent amylose and 70-80 per cent amylopectin. However, Chandrashekar (1985) reported the amylose content of sorghum starch to vary from 24 to 36 per cent of which water-soluble amylose ranged from 9 to 22 per cent.

Protein, fat and amylose contents of 14 sorghum cultivars were reported by Viraktamath *et al.* (1972) as ranging between 9.0-13.0, 1.9-3.8 and 23.6-28.9 per cent respectively. Subramanian and Jambunathan (1982) found the protein, fat, starch, total amylose and soluble sugars contents to vary from 8.0 to 14.1, 2.3 to 4.7, 62.6 to 73.3, 21.2 to 30.2 and 0.7 to 1.6 per cent respectively in 45 sorghum genotypes. Protein content showed a strong negative relationship with starch and water soluble amylose contents in the grain.

Okoh *et al.* (1982) observed comparatively little differences among the varieties of Nigerian sorghums in ash, crude fiber, fat and carbohydrate contents. In contrast, the crude protein and tannin contents showed considerable variation. Eggum *et al.* (1983) reported the protein, fat and starch content of sorghum from Sudan as 10.9-23.4, 4.0-5.1 and 71.0-73.4 per cent respectively.

Subramanian and Jambunathan (1984) reported the sorghum grain protein to vary from 4.4 to 21.1 per cent with a mean of 11.4 per cent and a significant negative correlation with starch content. Sreemannarayana (1984) observed significant differences in the protein content of certain released and pre-released cultivars of sorghum.

Polishing of sorghum reduces the fiber content by more than 50 per cent (Viraktamath *et al.*,1971). Chibber *et al.* (1978) reported considerable loss (up to 45 per cent) in protein as well as tannins (up to 98 per cent) due to dehulling. Studies of Eggum *et al.* (1983) have shown that the processing of sorghum into food reduces the energy digestibility in cooked compared to uncooked sorghum.

2.3 PHYSICAL PROPERTIES OF STARCH

The quality and uses of starch are controlled to a large extent by its physical and chemical properties. The physicochemical characteristics of starch are influenced by the amylose content in sorghum (Miller and Burns, 1970). The viscosity of starch paste is an important physical characteristic that determines its utilization in various foods (MacMasters and Wolf, 1959). More over, the viscosity data give valuable information concerning the physical changes that may be expected during the processing of a starch containing product (Waldt and Kehoe, 1959).

The bonding forces within the starch granule would influence the manner of swelling and the swelling pattern is greatly influenced by the species of starch (Leach *et al.*,1959). As the starch granule swell they become increasingly susceptible to shear. Also accompanying swelling, is an increase in soluble starch content (Kulp 1972). The swelling and solubility properties of sorghum starches are correlated with the amylose content of the starch (Akingbala *et al.*,1982). Subramanian *et al.*(1982) reported significant relationship between swelling power and solubility of sorghum starch at different temperatures with the cooking quality characteristics of boiled sorghum.

The gelatinization temperature of starch is influenced by starch granule size (Bathgate and Palmer, 1972), the proportion of amylose to amylopectin in starch (Hoseney *et al.*, 1981) and the presence of protein bodies around the starch granule (Chandrashekar and Kirleis, 1988). The gelatinization temperature of the waxy sorghum starch was higher than that of the non waxy starch in measurements by the differential scanning calorimeter (DSC). Whereas, the pasting temperature or apparent gelatinization temperature of the non waxy starch was higher by the Viscoamylograph. However, the isolated starches have narrower pasting temperatures than the unisolated starches (Akingbala *et al.*, 1982).

In rice, the ratio of the starch fractions (amylose to amylopectin) along with the protein was established to have the major influence on cooking and eating quality of the grain (IRRI, 1979; Juliano *et al.*, 1972, 1981; Juliano *et al.*, 1965). According to Desikachar (1975), Ali and Wills (1980), high gelatinization temperature in sorghum has been considered as an undesirable property, because it prolongs the cooking time of sorghum during processing.

Badi *et al.* (1976) reported similar pasting properties in millet starch as those of sorghum starch, except during the one hour holding period at 95^{o}C. Belelia *et al.* (1980) observed variations in gelatinization temperature, amylograms of starch isolated from five random-mating populations of pearl millet. Comparisons were made of water absorption (WAI), water solubility (WSI), and Brabender amylograph patterns of the roll-cooked small grain products from wheat, barley, rye, corn, sorghum and oats (Anderson, 1982).

Abd-Allah *et al.* (1986) reported a higher set back viscosity (retrogradation) in sorghum starch than corn and pearl millet starches. Subramanian *et al.* (1992) observed a higher paste consistency in sorghum starch than corn starch. Swelling power was greater for sorghum starch than for corn starch. However, the solubility of corn starch was comparatively higher than sorghum starch.

The inherent water solubility properties of corn and sorghum starches were studied by Jackson *et al.* (1989) with high-performance size-exclusion chromatography (HPSEC). Jane and Chen (1992) investigated the effects of amylose and amylopectin structures on functional properties of starch. Synergistic effects on paste viscosities were observed when the reconstituted starches were made with mixtures of amylose and amylopectin.

2.3.1 Role of lipids on physical properties of starches

Monoacyl lipids are known to play a major role in the paste and gel behaviour of wheat and corn starches (Eliasson, 1986; Dengate, 1984; Morrison and Milligan, 1982). Lipid removal from barley and corn starches gave a some what reduced pasting temperature, negligible pasting peak, improved cooking stability and reduced set back (Goering *et al.*, 1975). They attributed these changes to an amylose-lipid complex in the native starches. According to Melvin (1979) lipid removal from corn and wheat starches reduced the pasting temperature but increased the pasting peak, paste consistency, and set back.

Lipid removal from the oat starch resulted in a marked reduction of swelling power and an increase in solubility (Doublier *et al.*, 1987). When prime wheat starch was impregnated with 2 per cent wheat starch lipids, the pasting peak and consistency in the amylograph increased and a strong second peak was observed during the cooling cycle (Takahashi and Seib, 1988).

2.4 POPPING QUALITY

Popped sorghum is a popular snack food in sorghum growing regions of India (Viraktamath *et al.*,1972) and Africa. Popping can be an economic and effective method for processing millets for food and industrial uses. The popped sorghum grains can be used in weaning and supplementary food formulations (Malleshi, 1989).

Popping volume, defined as volume per unit weight of a sample, is a primary characteristic of popcorn, since commercial buyers purchase it by weight and sell by bulk volume. Furthermore, popcorn texture (tenderness and crispness) is positively correlated with popping volume (Rooney and Serna-Saldivar, 1987).

Viraktamath *et al.*(1972) reported considerable variation among sorghum cultivars for popping quality. Viraktamath and Desikachar (1972) considered the identification of cultivars which possess inherent superior popping quality is useful for breeders for development of high yielding cultivars suitable for popping. Prasada Rao and Murty (1982) identified several land races of sorghum for their superior popping quality. Preliminary studies on association of some grain characters with popping quality and the inheritance of popping quality in sorghum indicated that the character is under polygenic control (Murty *et al.* 1983). Murty *et al.* (1988) in their study indicated the presence of significant dominance and dominance x dominance type of interactions in the inheritance of pop volume.

Moisture content has been considered the most critical factor in popping, because it affects the rate and extent of pressure build up in starch granules (Eldredge and Lyerly, 1943; Eldredge and Thomas, 1959; Hoseney *et al.*, 1983). Haugh *et al.* (1976) indicated that the optimum moisture content was different for different hybrids of popcorn. In addition, the method of popping is expected to influence the optimum moisture content. Metzger *et al.* (1989) found a higher popped volume in hot air popping than oil popping. A greater moisture content was needed for hot-air popping in corn. Thorat *et al.* (1990) observed higher percentage of popping in sorghum grains with 18 per cent moisture and higher popped volume and expansion in grains with 15 per cent moisture.

Previous studies have shown that the physical properties of popcorn such as kernel size, shape and density affect expansion volumes during popping (Lyerly, 1942; Richardson, 1959; Ayyangar and Ayyer,1936; Eldredge and Thomas, 1959). Lein and Haugh (1975) reported a proportional relationship of expansion volume of popcorn with the severity of kernel damage. Haugh *et al.* (1976) found that the expansion volume of popcorn by oil popping was influenced by bulk density and sphericity but not by kernel size and shape.

According to Murty *et al.* (1982) good popping sorghum grains are characterized by a small grain size, medium thick pericarp, hard endosperm and a very low germ, endosperm ratio. Thorat *et al.* (1988) reported significant positive relationship between expansion ratio of pops, seed hardness and bulk density in sorghum cultivars. Pop yield also had strong positive correlation with the seed hardness. Kasturiba *et al.* (1989) reported the popping quality of 7 new varieties of sorghum.

Lin and Anantheswaran (1988) reported that the expansion volume of popcorn in microwave popping increased with kernel size but kernel size had no significant effect on unpopped kernel ratio. Dofing *et al.* (1990) observed a significant genotype x popping method interaction for expansion volume, flake size and percentage of unpopped kernels in corn genotypes. Pordesimo *et al.* (1990) and Song *et al.* (1990) showed that the kernel size of popcorn significantly affected the popping volume and the number of unpopped kernels. Whereas, Murugesan and Bhattacharya (1991) observed a positive relationship between grain hardness in paddy and popping expansion of rice.

However, the relationship of starch qualities to expansion properties of cereals are not completely understood. Earlier workers Matz (1959), Mottern *et al.* (1967), Srinivas *et al.*(1974),Viraktamath *et al.* (1972) and Malleshi and Desikachar (1981) reported that amylose content was not related to popping quality in cereals. Whereas, Chinnaswamy and Bhattacharya (1983) reported a significant relationship between total amylose and expansion ratio of puffed rice. Mercier and Fillet (1975), Chinnaswamy and Hanna (1988) observed that starch content and quality factors (amylose and amylopectin) most significantly affect the expansion properties of extruded products.

2.5 FLAKING QUALITY

A popular form of ready-to-eat breakfast cereal is the crisp flake. Breakfast cereal manufacture was originally an art, and quite proprietary, with relatively few publications except for patents (Daniels, 1974). Number of different processes are used in the preparation of ready-to-eat cereals including flaking, puffing, shredding, and granule formation of wheat, corn and rice, but none of sorghum (Kent, 1983). The studies on flaking of sorghum are limited and hence citations from rice and maize are given.

Lu and Walker (1988) developed a process for making ready-to-eat breakfast flakes from grain sorghum flour using simple and low technology process. Sensory evaluation and consumer study of these flakes indicated that they were palatable and acceptable to many people.

According to Ananthachar (1982) soaking of paddy in water, roasting in hot sand and tempering followed by flaking in edge-runner were found to be optimal for flaking of rice. Narasimha *et al.* (1982) developed a continuous process for making rice flakes from paddy. Shankara *et al.* (1984) found that the small roller flaker with the edge-runner will facilitate fine flaking of coarse flakes and increase the yield of rice flakes.

Sukhonchun-Sringam and Chumsai-Silawanit (1982) prepared flakes from cooked corn grits by pair of rollers usually used for wheat noodles sheeting and evaluated for the acceptability. Moisture content in flaked corn was reduced before deep fat frying. Their results showed that plain, sugar frosted and powder sugar coated flakes were all well acceptable. Simon Food Engineers Ltd (1985) utilized fine maize grits (250 µm size) as raw material for the preparation of quality maize flakes.

Chigumira (1988) discussed the preparation of extrusion cooked ready-to-eat maisoy-sorghum puffed flakes using Brady extruder. In the high protein ready-to-eat maisoy-sorghum puffed flakes, sorghum levels above 20 per cent gave a product with a gritty texture, unacceptable color and flavor and limited expansion.

Fast (1987) reported an overview of cereal flaking process including description of the preparation of cooked grits or pellets for flaking. Fast *et al.* (1990) discussed the process by which cooked and tempered grits or extruded pellets are made into thin flakes that were toasted into crisp golden-brown corn flakes, wheat flakes or rice flakes. Papotto *et al.* (1990) reported the development and quality evaluation of extrusion cooked corn-buck wheat ready-to-eat flakes.

2.6 ORGANOLEPTIC EVALUATION OF POPS AND FLAKES AND OBJECTIVE MEASUREMENT OF TEXTURE

Very limited literature is available on the organoleptic evaluation and instrumental (objective) methods of measuring texture of pops and flakes. Iles and Elsen (1972) found a high correlation between textural preferences and sensory crispness, indicating that the acceptability of a food's texture increased with increasing crispness. Sensory evaluation and consumer study of flakes prepared from grain sorghum flour indicated that they were palatable and acceptable to many people (Lu and Walker, 1988).

Vickers (1983) observed that crispness was closely associated with the pleasantness of biting sounds. Vickers (1985) have used a bite test cell in an Instron Universal Testing Machine to determine the force - deformation behaviour of eight ready-to-eat breakfast cereals and potato chips. Seymour (1985) used a Kramer shear cell in an Instron to crush samples of several dry crisp foods altered in crispness by humidification. The measurements of peak force, slope and area under the force - deformation curve had small negative correlations with sensory crispness (Vickers 1987).

2.7 INFLUENCE OF PROCESSING ON *IN VITRO* STARCH DIGESTIBILITY

The digestibility of starch is affected by the composition and physical form of starch, protein - starch interactions, the cellular integrity of the starch - containing units, anti-nutritional factors and the physical form of the feed or food material (Thorne *et al.*, 1983; Dreher *et al.*, 1984; Rooney and Pflugfelder, 1986 and Waniska *et al.*, 1990). Processing increases the enzymic availability of starch to different extents. An increased availability may be attributed to several factors such as gelatinization, disruption of the protein structures and cell walls encapsulating starch, expansion and physical disruption of the sample (Holm *et al.*, 1985). Quantifying the effect of processing on the digestibility of dietary components will enable researchers to relate the compositional changes to the resulting nutritional response.

Osman *et al.* (1970) reported that flaking of barley or sorghum grain after steaming at atmospheric pressure or at pressures of 1.4 to 5.6 kg $cm^{2\ -1}$ markedly increased enzymatic starch digestion of both grains. Fredrick *et al.* (1973) observed that enzymatic starch degradation was higher for processing treatments involving application of moisture, heat and pressure. Mercier and Fillet (1975) found an increase in susceptibility of cereal starches to bacterial α-amylase with increasing extrusion temperature. Starch granule structural changes and amylolytic patterns in steam flaked, microionized and popped sorghum grain were studied using scanning electron microscope (Harbers, 1975).

In a study on sorghum, McNeill *et al.* (1975) observed greater digestion after flaking compared to microionising. This was due to the release of starch from protein matrix, indicating that gelatinization alone is not the only factor involved in increasing the starch susceptibility to enzyme action. Farber and Gallant (1976) observed that, after flaking of barley and maize, the protein matrix seemed to be reticulated and fragmented, and after popping, it appeared to be stretched.

In another investigation, it was shown that the extrusion of wheat greatly increased the initial amylolysis rate and the proportion of easily hydrolysable starch to 79 per cent. Whereas, popping and flaking gave some what lower values, 56 and 52 per cent, respectively (Delort-Laval and Mercier, 1976). Colonna *et al.* (1984) observed macromolecular degradation of wheat starch, without formation of oligosaccharides, during extrusion cooking.

In an *in vitro* assay using hog pancreatic α-amylase after pre incubation with pepsin, starch in flaked wheat was less digestible than that in boiled, popped and steam cooked wheat (Holm *et al.*, 1985). The availability of starch to porcine pancreatic α-amylase after extrusion cooking, drum drying, popping, dry autoclaving and steam flaking of wheat was studied by Holm and Bjorck (1988).

2.8 INFLUENCE OF PROCESSING ON *IN VITRO* PROTEIN DIGESTIBILITY

The quality of a protein depends on the amount and proportions or balance of the essential amino acids which are absorbed, in relation to the needs for such amino acids by the animal organism. Though considerable attention has been paid to the crude protein and gross energy content in various dietary sources, less information is available on the digestibility of the respective protein and energy sources.

The published information available on the apparent digestibility of sorghum proteins indicates that they are less digestible than those of other cereals (Kurien *et al.*, 1960; MacLean *et al.*, 1981; Nicol and Phillips, 1978). Numerous comparisons of sorghum cultivars have been made using *in vitro* digestibility methods (Hahn *et al.*, 1982; Hibberd *et al.*, 1982). Hulse *et al.* (1980) reported 84 per cent digestibility in African x Indian sorghum varieties. Whereas, African varieties alone were observed to be only 66 per cent digestible.

Earlier workers (Ramachandra *et al.*, 1977; Chibber *et al.*,1980; Hulse *et al.*, 1980) reported the favourable effect of dehulling on IVPD of cereals and millets. Roy (1985) reported an increase in IVPD of sorghum by 8 per cent on dehulling.

Heat processing of cereals and millets has been found to reduce IVPD. Preparation of breakfast cereals was found to reduce the protein quality of processed cereal products (Eggum, 1978). Axtell *et al.* (1981) using an *in vitro* pepsin assay found that uncooked sorghum proteins had a high digestibility (78-100 per cent), which dropped to a range of 45-55 per cent after cooking.

Mertz *et al.* (1984) using a modified pepsin digestibility procedure, found that the digestibility of cooked sorghum gruel was lower than that of cooked gruels made with wheat, maize, rice and millet. They also reported that the pepsin protein digestibility of decorticated, heat-extruded sorghum was higher than for whole sorghum gruels. These findings are in agreement with the *in vitro* protein digestibility results reported by MacLean *et al.* (1983) and Graham *et al.* (1986) for the same processed sorghum foods. Bradbury *et al.* (1984) reported 11 per cent decrease in IVPD due to boiling of rice. The IVPD of cereals/millets reported by Rajyalakshmi (1986) indicated a reduction of 10 to 22 per cent in IVPD of cereals/millets due to boiling. Roy (1985) reported that processes like parching, popping, parboiling and preparation of roti and biscuits showed no loss in IVPD as compared to whole grain sorghum.

The deleterious effect of Parboiling on IVPD of cereals has been reported by Kato *et al.* (1983). Rajyalakshmi (1986) however, did not show marked variation between IVPD of raw and parboiled finger millet (*Setaria italica*).

Hamaker *et al.* (1986) indicated a significant decrease in sorghum protein digestibility following cooking and observed that kafirins are the predominant indigestible proteins in cooked sorghum. Hamaker *et al.* (1987) showed that the sorghum digestibility decreased by 24.5 per cent after cooking which was a significantly greater decrease than for maize, barley and rice. Hakansson *et al.* (1987) reported that the mildly heat-treated whole grain wheat was significantly more digestible than the raw sample. Whereas, popping resulted in a greater decrease in biological value and net protein utilization.

In vitro protein digestibility improved in popcorn and sweet corn kernels after popping and boiling respectively, whereas, it decreased slightly in normal and opaque-2 maize following these treatments (Gupta *et al.*,1986). Extrusion cooking improved the protein digestibility of 2 low tannin sorghums (Fapojuwa *et al.*, 1987).

Kamini Devi (1990) in her study observed a higher reduction in protein digestibility of sorghum on heat processing due to its cross linked prolamine content compared with rice and pearl millet. However, the sorghum protein digestibility *in vitro* was better on popping (36.5 per cent) than with boiling (31.2 per cent), baking into biscuit (31.7 per cent) and roti (29.2 per cent).

MATERIALS AND METHODS

CHAPTER III

MATERIALS AND METHODS

Grain samples of 20 cultivars with a range in endosperm texture were selected in the present study. These cultivars represent high yielding varieties/hybrids and local cultivars suitable for the agro-climatic conditions of Andhra Pradesh, India. The details of the cultivars are given in Table 1.

The aspects studied were:

- o Physicochemical characters of whole grains, pops and flakes.
- o Swelling, solubility and pasting properties of isolated starch and pasting properties of flour.
- o Standardisation of popping and flaking methods.
- o Sensory evaluation of pops and flakes.
- o *In vitro* starch and protein digestibility of grain, pops and flakes.

3.1 GRAIN SAMPLE

The grain samples of the cultivars except SPV 475 and yellow sorghum were provided by the National Research Centre for Sorghum (NRCS), Hyderabad, India. Yellow sorghum (local variety) was purchased from the local wholesale market. SPV 475 was provided by ICRISAT, Patancheru, India. Fourteen of these cultivars were grown during the 1990/91 postrainy season (rabi) and the remaining 6 cultivars were grown during the 1991 rainy season (kharif).

Table 1: Description of cultivars selected for the study.

Cultivar	Description
M 35-1	A popular local variety in India.
SPV 475	Rainy season variety released in India in 1988.
SPV 504	Postrainy season variety popularly known as Swati.
SPV 783	Postrainy season variety with bold grains.
SPV 913	Early maturing, postrainy variety. Released in Andhra Pradesh as NTJ-2.
SPV 980	Postrainy season variety with small grains.
SPH 504	High yielding, postrainy season hybrid with good fodder yield.
CSH 12R	Postrainy season hybrid.
CSV 8R	Postrainy season variety with bold grains.
CSV 8R Mutant	High protein, high lysine shriveled mutant.
P 721	Normal plumpy, high lysine line from Purdue University (USA).
P 721 Mutant	Shriveled mutant having high protein and lysine.
Nizamabad	Postrainy season variety with bold grain.
Yellow sorghum (Local)	Yellow grain variety normally grown in Rayalseema.
CSH 1	Short duration, rainy season hybrid with bold grains.
CSH 5	Rainy season hybrid, released in 1974.
CSH 6	Short duration, rainy season hybrid released in 1977.
CSV 10	Released variety suitable for rainy season.
CSV 11	Rainy season variety released in India in 1984.
SPH 468	An early maturing, rainy season hybrid released in Akola.

3.2 PREPARATION OF SAMPLE

The grains were cleaned to remove extraneous material and sundried for two consecutive days to prevent the grain from insects and moulds.

3.3. PHYSICAL METHODS

The grains of each cultivar were equilibrated in an incubator at 37°C for 4-5 days to a moisture content of 8.0±0.5% and evaluated for various physical characteristics.

3.3.1 100-grain mass

One hundred whole grains were randomly selected and weighed (± 0.01 g) in three replications and the mean values were recorded.

3.3.2 100-grain volume

Absolute volume of 100 grains was determined by the xylene displacement method of Reyes *et al.* (1965). The mean of three replications were recorded.

3.3.3 Grain dimensions

The length, width and thickness of 20 grains were measured using a vernier calipers. The mean of 20 measurements were recorded as representative of the cultivar.

Length (l) is defined as the distance from the tip cap to the kernel crown.

Width (w) is defined as the widest point to point measurement taken parallel to the face of the kernel.

Thickness (t) is defined as the distance between the two kernel faces.

3.3.4 Endosperm texture

Ten Grains were cut longitudinally using a razor blade. The grain halves were evaluated subjectively for the percentage area of floury endosperm to the total endosperm. Mean of three individual evaluations were recorded.

3.3.5 Grain hardness

3.3.5.1 Stenvert hardness

Grain samples of 18 g (± 0.01 g) were ground to pass through 2.0 mm screen in a Glen-Creston Stenvert hardness tester (Glencreston mills, England), as described by Pomeranz *et al.* (1985). The time (seconds) required to collect 17 ml of whole meal was recorded as resistance to grinding. The first run for each sample was deleted because the grinding chamber and screen were cleaned between samples. Three replicates were made and the mean values recorded.

3.3.5.2 Kiya hardness

Kiya hardness was measured on individual grains as crushing force (kg $sq.cm^{-1}$) using a Kiya hardness tester (Kiya Seisakusho, Ltd, Japan). The average of 20 determinations were recorded.

3.3.6 Floaters Percentage

Floaters percentage was determined by the method of Hallgren and Murty (1983), by employing density grading in sodium nitrate solution (specific gravity 1.315 g ml^{-1} at $25^{o}C$). The tests were performed on samples of 100 grains. The average number of floating grains from three replications were recorded for each cultivar.

3.3.7 Bulk density

Bulk density is defined as the ratio of grain weight (g) to the apparent volume of grains (ml). Apparent volume of 100 g of grains was measured using a graduated measuring cylinder.

$$\text{Bulk density} = \frac{\text{Weight of the sample (g)}}{\text{Volume of the sample (ml)}}$$

3.3.8 Dehulling recovery

Weighed samples (20 g $\pm$ 0.01 g) were dehulled as per Reichert *et al.* (1986) for 6 minutes using a Tangential Abrasive Dehulling Device (TADD model 4E-230, Venables Machine Works Ltd., Canada) fitted with 100 grit, 10" diameter, shur-stick resine bound disc mounted horizontally, on the shaft of electric motor (1/20 HP., 110 V.A.C., 1725 R.P.M). The dehulled grain samples were collected in the sample aspirator trap fitted with a 20 mesh screen, and weighed.

$$\text{Dehulled grain recovery (\%)} = \frac{\text{Weight of dehulled grains}}{\text{Weight of whole grains}} \times 100$$

3.3.9 Water absorption capacity

A 10 g (± 0.01 g) sample of dehulled grains were soaked in distilled water for 4 hrs at room temperature. Grains were surface dried after removal from the beaker and weighed (Hsu *et al.* 1983). Water absorption capacity is defined as the increase in weight due to absorption of water.

3.4 STANDARDIZATION OF POPPING METHOD

Conditioning of grain: In order to establish an optimum moisture level for popping, the grain samples of yellow sorghum (local variety) and SPV 475 were adjusted to different moisture contents ranging from 8-18 per cent with an increment of 2 per cent. Initially, the grain samples were dried in an oven at 37°C for 2-3 days to equilibrate the moisture to 8 per cent. Moisture content was increased to 18 per cent by spreading the grains in a tray and exposing in a humidity chamber maintained at 95% RH and 30°C temperature. Grain moisture was determined periodically until the samples absorbed the required amount of moisture. The effect of tempering time on the moisture content of the samples is given in Table 2.

Table 2: Effect of tempering on grain moisture content

S.No.	Sample treatment	Moisture (%)
1	control (untreated)	8.0±0.5
2	tempered for 2 hours	10.0±0.5
3	tempered for 5 hours	12.0±0.5
4	tempered for 8 hours	14.0±0.5
5	tempered for overnight	16.0±0.5
6	tempered for 1 day with added water	18.0±0.5

A locally manufactured corn popper (Metro, India) equipped with a thermostat and motor driven stirrer was used to pop the grains. Preliminarily experiments were conducted to determine the optimum sample size (50-250 g), temperature (240-300^{o}C) and popping time (1-3 minutes) for better popping. Grain sample size of 50 g, 240^{o}C popping temperature and 2 minutes popping time were chosen, since this yielded the highest popped volume, popping percentage and good overall appearance of the popped product.

To determine the optimum moisture content of the sample for better popping quality, 50 g samples of SPV 475 and Yellow sorghum were popped at different moisture contents (8, 10, 12, 14, 16 and 18 per cent) for 2 minutes at 240^{o}C in three replications. The pops were evaluated for their popping per cent, popped volume, expansion ratio and expansion volume (Table 3) as given in Section 3.5.

Table 3: Popping quality of sorghum at different moisture levels.

Cultivar	Moisture content (%)	Popping per cent	Popped volume (ml)	Expansion volume ($ml\ g^{-1}$)	Expansion ratio
YELLOW SORGHUM					
	8	53	182	3.6	3.1
	10	64	297	5.9	5.1
	12	85	427	8.5	7.4
	14	89	568	11.4	9.8
	16	91	593	11.9	10.2
	18	88	500	10.0	8.6
SPV 475					
	8	42	204	4.0	3.4
	10	42	255	5.1	4.3
	12	54	347	7.0	5.8
	14	57	367	7.3	6.1
	16	69	415	8.3	6.9
	18	53	407	8.1	5.8

Values are the mean of three determinations

Grain samples of 20 cultivars were popped at 16 per cent moisture level and 240^{o}C for 2 minutes. Each cultivar was popped in three replications and the mean values were recorded.

3.5 PHYSICAL PROPERTIES OF POPS

3.5.1 Popping per cent

The popped and unpopped grains were separated using 12/64" round sieve (Seedburo equipment Co., USA). The number of popped and unpopped grains were counted and expressed as percentage.

$$\text{Popping per cent} = \frac{\text{Number of popped grains}}{\text{Total number of grains}} \times 100$$

3.5.2 Popped volume

The volume of 50 g popped sample was measured using a graduated measuring cylinder.

3.5.3 Expansion volume

Expansion volume is defined as the popped volume divided by its original grain weight.

$$\text{Expansion volume} = \frac{\text{Total popped volume (ml)}}{\text{Original grain weight (g)}}$$

3.5.4 Expansion ratio

Expansion ratio is determined by the ratio of bulk volume of popped sample to that of raw sample.

$$\text{Expansion ratio} = \frac{\text{Bulk volume of popped sample (ml)}}{\text{Volume of raw sample (ml)}}$$

3.5.5 Crispness of sorghum pops

The crispness of sorghum pops was measured as described by Bourne *et al.* (1966), using an Instron Universal Testing Machine equipped with Kramer shear cell and 500 kg capacity load cell. Grains of SPV 475 and yellow sorghum were popped at different moisture levels and used for standardization of texture measurements. A 2.5 g homogeneous pops were packed in a Kramer shear cell and the force required to crush the pops was recorded on a chart recorder operating at cross head to chart speed of 2:1. The force required to crush the pops was measured in 3 replications and the average values were recorded. Crispness of pops was expressed as force (kg $sq.cm^{-1}$) per gram of pops.

3.6 STANDARDIZATION OF FLAKING METHOD

A series of experiments were conducted in Defence Food Research Laboratory (DFRL), Mysore, using whole and dehulled sorghum grains to optimise the process conditions for the preparation of flakes. The whole grain sorghum yielded rough and dull coloured flakes having bran on the surface of the flakes. Hence, the removal of bran is necessary to achieve desirable sensory properties.

3.6.1 Dehulling

The grains were dehulled for 6 minutes using a Tangential Abrasive Dehulling Device fitted with 100 grit size, 10" diameter resin bound disc mounted horizontally on the shaft of an electric motor.

3.6.2 Soaking

To obtain optimum soaking time, 500 g batches of dehulled grains of yellow sorghum and SPV 475 were soaked in water for different periods ranging from 1-24 hrs. Moisture content of grains was determined at different soaking periods and 3-4 hours soaking time was observed to be optimum.

3.6.3 Cooking

The soaked grains of yellow sorghum and SPV 475 were cooked in an ordinary autoclave at 15 and 20 pounds per square inch (psi) pressure for 20, 30 and 40 minutes to determine the optimum cooking time and pressure per square inch. The degree of cooking was evaluated by pressing the cooked grains between two glass slides. The absence of uncooked hard-core indicates the completion of cooking. The grains cooked at 20 psi pressure for 20 minutes showed the complete disappearance of uncooked hard core. The moisture content of the cooked grains was approximately 34 per cent.

3.6.4 Conditioning

The cooked grains were conditioned to 25-28 per cent moisture content by drying in a cabinet drier at 70^{o}C temperature (for few minutes) and further conditioned for 1 hr at room temperature.

3.6.5 Flaking

The conditioned sorghum grains were passed through heavy duty flaking rolls (L & T Turner Ipswich model, TER and F Turner Ltd, England) of 24" long and 18" diameter, rotating at a speed of 70-80 rpm to process them into flakes. The distance between the rolls was adjusted to 0.5 mm to yield thin flakes.

3.6.6 Drying

The flakes were dried in a cabinet drier at 70^{o}C for about 1 hr to reduce the moisture content.

Flow diagram of Sorghum Flaking Process

```
Dehulling
   |
   |
   |
Soaking in water
   |
   |(3-4 hrs at room temperature)
   |
Pressure cooking
   |
   |(20 psi for 20 minutes)
   |
Conditioning
   |(Drying at 70°C for a few minutes
   | followed by drying at room
   | temperature for 1 hr)
Flaking
   |
   |
   |
Drying at 70°C for 1 hr.
   |
   |
   |
Packing
```

3.7 PHYSICAL PROPERTIES OF FLAKES

3.7.1 Bulk density

Volume of 100 g flakes was measured using a graduated measuring cylinder. The bulk density of flakes was calculated and expressed in g L^{-1}.

$$\text{Bulk density} = \frac{\text{Weight of sample (g)}}{\text{Volume of the sample (L)}}$$

3.7.2 Yield of flakes

Flakes were passed through 8/64" round (commercial) sieve to separate brokens and powder. The yield of flakes was expressed as percentage.

3.7.3 Water absorption capacity

Water absorption capacity of sorghum flakes was measured by weighing the water uptake of 2 g of flakes at room temperature for 10 minutes. The values were expressed as g $100g^{-1}$ of flakes.

3.8 STARCH PROPERTIES

3.8.1 Starch isolation

Starch was isolated from whole grains by the steeping and wet milling procedure of Watson *et al.* (1955) with minor modifications.

3.8.2 Swelling Power and Solubility

Swelling power (g g^{-1}) and solubility (%) of the starch at different temperatures (70°C, 80°C and 90°C) were determined following the method of Schoch (1964). Starch (0.5 g) was heated with 20 ml water to 70°C, 80°C and 90°C for 30 minutes. The lump formation was prevented by stirring constantly with glass rod. The mixture was centrifuged at 5000 x g for 10 minutes. The supernatant was carefully removed and the swollen starch sediment weighed. Swelling power is the ratio in mass of the wet sediment to the initial mass of the dry starch. A 10 ml aliquot of supernatant was evaporated overnight at 110°C and weighed. The mass was corrected to the volume of supernatant and initial mass of the dry starch and expressed as per cent soluble starch. The experiment was carried out for three times and the mean values were recorded.

3.8.3 Viscoamylography of sorghum flour and starch

Pasting properties of flour and isolated starches were determined by the method of Smith (1964), with a Brabender Viscograph-E (Model R-302, C.W. Brabender instruments, Inc., Haccensack, NJ) operated with a bowl speed of 75 revolutions per minute (rpm). The flour concentrations of 10 per cent or starch concentrations of 8 per cent on moisture free basis, in 450 ml distilled water was used. The Flour/ starch slurry was heated from 30°C to 95°C with an increment of 2°C per minute, held at 95°C for 60 minutes, then gradually cooled to the original start temperature at the same rate as in heating.

Initial and final temperatures of pasting, peak viscosity, viscosity at 95°C, breakdown viscosity and set back viscosity at 50°C and 40°C were determined. The values were recorded as mean of two determinations.

3.9 CHEMICAL METHODS

Whole grain samples were ground into flour in a Udy cyclone mill (Udy Corp; Colorado, USA) to pass through a 0.4

mm screen. Pops and flakes were ground using Krupes blender. The samples were defatted in a Soxhlet apparatus with n-hexane prior to analysis. All the analysis were carried out in duplicates and the mean values were recorded.

3.9.1 Moisture

Moisture content was determined by loss in weight following drying the sample in a forced draft hot air oven at 100 $\pm$ 5^{o}C for overnight (AOAC, 1984).

3.9.2 Protein

Protein content was determined by digesting the sample (100 mg) in a block digestor (BD 40) with 3 ml acid mixture (5 parts orthophosphoric acid and 95 parts H_2SO_4) and one kjel tab (each tablet containing 1.5 g potassium sulfate and 7.5 mg selenium). The digested sample was made up to 75 ml. The converted ammonical nitrogen was estimated using a Technicon Auto Analyser (TAA) by the method of Singh and Jambunathan (1980). Ammonium sulphate was used as standard. Protein values were calculated by multiplying the per cent of nitrogen with 6.25.

3.9.3 Starch

A 75 mg defatted sample was dispersed in 1 ml alchohol and autoclaved with 10 ml water at 19 psi pressure for 90 minutes. After cooling, 15 ml water was added and hydrolyzed for 2 hr at 55^{o}C by adding 1 ml of 2 M sodium acetate buffer and 25 mg amyloglucosidase (Sigma Chemical Co., Cat No. A7255). Starch on hydrolysis by amyloglucosidase was converted to maltose and finally to glucose. The sugar thus obtained was analyzed quantitatively using phenol-sulfuric acid reagent (Dubois *et al.*, 1956). Glucose (100 µg/ml) was used as standard. The percentage of starch present in different samples was obtained by multiplying the glucose concentration with 0.9.

3.9.4 Amylose

Total amylose content of starch in sorghum grain was determined as per Williams *et al.* (1958). A 100 mg defatted flour was dispersed with 1 ml 95% alchohol and extracted with 1N NaOH at 30°C for overnight. A 5 ml of the diluted extract was adjusted to pH 10.2 with dilute acid (0.1N HCl). The absorbance of the blue colour produced in aqueous solution by the addition of Tri-iodide ion (2% KI and 0.2% KIO_3 solution) was measured at 600 nm. Amylose (BDH) was used as the standard.

3.9.5 Total soluble sugars

A 100 mg of defatted flour was extracted thrice with 80% hot aqueous ethanol and evaporated the extract to minimum quantity. The volume was made upto 100 ml with water. One ml aliquot was pipetted out and the color developed with phenol-sulfuric acid reagent was read at 490 nm against a water blank (Dubois *et al.*, 1956). Glucose was used as standard. The values were expressed as per cent soluble sugars of flour.

3.9.6 Fat

Ground sample (5 g) was packed in a Whatmann No 2 filter paper and extracted the oil in a Soxhlet apparatus with n-hexane. The extracted oil was transferred to a preweighed beaker (250 ml) containing 3-4 boiling chips and evaporated the solvent on a sand bath. The beaker was reweighed. From the difference in weight, fat per cent of the sample was calculated. (The Official and Tentative Methods of the American Oil Chemist's Society ,1981).

3.9.7 Crude fiber

A 2 g sample in the presence of one gram asbestos was extracted sequentially for 30 min each with solutions of 1.25 per cent sulfuric acid and 1.25 per cent Sodium hydroxide. The extract was filtered using a California modified Buchner funnel (Labconco cat. No. 55100). The indigestible residue left after filtering was dried at 110°C for 2 hr and ashed in a muffle furnace at 600°C for 30 min. Crude fiber percentage was calculated (AOAC, 1984).

3.10 *IN VITRO* STARCH AND PROTEIN DIGESTIBILITY

3.10.1 *In vitro* starch digestibility

In vitro starch digestibility (IVSD) of ground sorghum samples was determined according to the method of Singh *et* *al.* (1982). A 50 mg defatted sample was dispersed in 1.0 ml, 0.2 M phosphate buffer (pH 6.9). To the sample suspension 0.5 ml pancreatic α-amylase (Sigma Chemical Co., CAT.No- 6880., 20 mg enzyme dissolved in 50 ml of the same buffer) was added and incubated at 37^{o}C for 2 hr. After the incubation period, 2 ml 3-5 dinitrosalicylic acid reagent was added immediately. The mixture was heated for 5 minutes in a boiling water bath. After cooling, the solution was made up to 25 ml with distilled water, and filtered prior to measurement of the absorbance at 550 nm. A blank was run simultaneously. A standard curve was prepared using maltose. Values were expressed as mg maltose released per gram sample.

3.10.2 *In vitro* protein digestibility

Defatted sample (250 mg) was incubated with 20 ml, 0.2 per cent pepsin (Sigma Chemical Co., Cat No. P 7000) in 0.1 M potassium dihidrogen phosphate buffer for 2 hr at 37^{o}C (Axtell *et al.*, 1981). After cooling, 5 ml 50 per cent TCA solution was added and centrifuged the contents at 10,000 RPM for 10 minutes. A 10 ml of the aliquot was evaporated to dryness and determined the protein per cent using TAA method. The per cent digestibility of protein of the total sample was recorded.

3.11 ORGANOLEPTIC EVALUATION

Sensory evaluation of pops and flakes followed the procedure of Larmond (1977). The taste panel members were selected from the responses received from triangle tests conducted with 15 members. The selected panelists were trained extensively using a standard check sample (yellow sorghum). The taste panel consisting of 9 trained personnel, evaluated the sorghum pops and flakes (with and without milk) made from 20 cultivars on 5 point scale for colour and appearance, texture, flavor and acceptability. Pops and flakes prepared from different cultivars and one standard (yellow sorghum) was included as a hidden check for taste panel evaluation. The mean scores of 9 panelists were recorded.

3.12 STATISTICAL ANALYSIS

The results of various physicochemical characteristics and physical properties of pops/flakes were statistically analyzed for correlation coefficients, stepwise multiple regressions and analysis of variance (Snedecor and Cochran, 1968). The statistical analysis was carried out using BASIC, GENSTAT and SAS programs. The histograms and graphics were prepared using Free-lance package.

EXPERIMENTAL RESULTS

CHAPTER IV

EXPERIMENTAL RESULTS

Physical and chemical properties are known to influence the processing and food-making qualities of sorghum grain. On processing, the various components of grain undergo some changes which were found to be beneficial and also detrimental to the quality. The present work was undertaken to study the relationship of popping and flaking quality with grain characteristics and *in vitro* starch and protein digestibility. The results are indicated in the following sections.

4.1 PHYSICAL PROPERTIES OF GRAIN

The physical properties of sorghum cultivars were determined after equilibrating the grains at 37^{o}C for 5 days. A few selected physical parameters of sorghum cultivars are given in Tables 4 and 5. One hundred grain mass ranged from 2.0 g (CSV 8R mutant) to 4.1 g (SPV 504) with a mean of 3.0 g. One hundred grain volume of cultivars varied between 1.5 ml (SPV 980) and 3.1 ml (SPV 504, SPV 783 and Nizamabad).

Among the cultivars CSV 8R mutant was found to have lower bulk density of 0.58 g ml^{-1} and SPV 980 had higher bulk density of 0.75 g ml^{-1}. Kernel dimensions ranged from 3.8 to 5.3, 3.3 to 4.6 and 2.2 to 3.4 mm for length, width and thickness respectively. The higher values for the three

Table 4: Physical properties of sorghum cultivars

Cultivar	100-grain[a] mass (g)	100-grain[a] volume (ml)	Bulk[a] density ($g\ ml^{-1}$)	Kernel dimensions (mm)[b] Length	Width	Thickness
M 35-1	3.4	2.6	0.73	5.3	4.6	3.4
SPV 475	2.3	1.8	0.72	4.2	3.7	2.5
SPV 504	4.1	3.1	0.71	4.9	4.3	3.1
SPV 783	4.0	3.1	0.72	5.0	4.2	3.0
SPV 913	3.7	2.9	0.73	5.0	4.3	2.8
SPV 980	2.1	1.5	0.75	4.1	3.4	2.2
SPH 504	2.8	2.2	0.73	4.5	3.7	2.6
CSH 12R	3.8	3.0	0.74	5.1	4.1	3.0
CSV 8R	3.6	2.7	0.73	4.7	4.0	2.8
CSV 8R Mutant	2.0	1.8	0.58	4.6	3.7	2.3
P 721	2.3	1.8	0.69	4.5	3.7	2.2
P 721 Mutant	2.1	1.9	0.61	4.7	3.9	2.2
Nizamabad	3.9	3.1	0.73	4.9	4.5	3.1
Yellow Sorghum	3.0	2.3	0.74	4.7	3.8	2.7
CSH 1	3.2	2.3	0.71	5.0	4.1	2.8
CSH 5	2.5	2.0	0.73	4.2	3.8	2.7
CSH 6	2.7	2.1	0.73	4.3	3.8	2.7
CSV 10	3.1	2.7	0.70	5.0	3.9	2.7
CSV 11	2.1	1.8	0.74	3.8	3.3	2.3
SPH 468	3.1	2.5	0.72	4.5	3.9	2.9
Minimum	2.0	1.5	0.58	3.8	3.3	2.2
Maximum	4.1	3.1	0.75	5.3	4.6	3.4
Mean	**3.0**	**2.4**	**0.71**	**4.7**	**3.9**	**2.7**
SE ±	0.16	0.12	0.984	0.09	0.07	0.08

a Values are mean of three determinations.
b Values are mean of twenty measurements.

Table 5: Physical properties and dehulling recovery of sorghum cultivars

Cultivar	Grain hardness		Per cent[a] floaters	Endosperm[c] texture (% Flouri-ness)	Dehulling[a] recovery (%)	Water[a] absorption capacity (%)
	Stenvert[a] (sec)	Kiya[b] (kg sq.cm^{-1})				
M 35-1	5.6	5.7	47	58	90.4	34.9
SPV 475	9.8	8.3	30	43	93.1	33.3
SPV 504	6.2	7.5	31	50	90.1	34.4
SPV 783	8.0	7.1	21	48	90.9	31.7
SPV 913	9.0	9.5	27	42	91.9	33.5
SPV 980	11.0	8.1	20	22	92.4	32.3
SPH 504	6.6	6.8	53	53	90.4	34.6
CSH 12R	7.4	6.6	43	72	90.7	36.8
CSV 8R	5.8	6.2	35	53	89.7	36.9
CSV 8R Mutant	5.4	4.2	100	93	67.8	73.5
P 721	9.1	7.0	63	58	91.7	33.2
P 721 Mutant	4.5	3.6	100	90	65.9	64.2
Nizamabad	6.1	6.1	67	58	90.0	37.4
Yellow Sorghum	9.3	7.2	19	40	91.5	33.6
CSH 1	9.1	6.5	53	40	90.8	32.4
CSH 5	7.8	6.0	60	48	88.3	35.9
CSH 6	9.7	7.9	42	48	90.2	32.0
CSV 10	8.3	7.3	67	45	90.8	33.9
CSV 11	11.9	9.4	25	40	92.4	32.8
SPH 468	8.3	7.5	60	60	91.8	35.6
Minimum	4.5	3.6	19	22	65.9	31.7
Maximum	11.9	9.5	100	93	93.1	73.5
Mean	**7.9**	**6.9**	**49**	**53**	**88.5**	**37.7**
SE ±	0.44	0.33	5.4	3.7	1.68	2.44

a Values are mean of three determinations.
b Values are mean of twenty determinations.
c Values are mean of three individual evaluations.

kernel dimensions being observed in M 35-1.

Resistance to grinding in the Stenvert hardness tester was lower for P 721 mutant (4.5 seconds) and higher for CSV 11 (11.9 seconds). Breaking strength of grains as determined by Kiya hardness tester varied from 3.6 to 9.5 kg sq.cm^{-1} with a mean of 6.9 kg sq.cm^{-1}. The percentage of floating grains in sodium nitrate solution ranged from 19 per cent (yellow sorghum) to 100 per cent (P 721 mutant and CSV 8R mutant). Percentage of floury endosperm (endosperm texture) ranged from 22 to 93 per cent with a mean of 53 per cent.

Total recovery of the dehulled grains (using Tangential Abrasive Dehulling Devise) varied between 65.9 per cent (P 721 mutant) and 93.1 per cent (SPV 475) with a mean of 88.5 per cent. SPV 783 had lower water absorption capacity (31.7 per cent) and CSV 8R mutant had higher water absorption capacity (73.5 per cent) among the cultivars.

Table 6 gives the correlation coefficients among different physical properties of sorghum. Correlation coefficients between 100-grain mass and other physical properties were relatively low and insignificant. Bulk density had significant positive correlation with grain hardness (Stenvert and Kiya), dehulling recovery and negative correlation with endosperm texture, floaters percentage and water absorption capacity.

Table 6: Correlation coefficients (r) among physical properties of sorghum cultivars

	Stenvert hardness	Kiya hardness	Per cent floaters	Endosperm texture	Bulk density
100-grain mass	-0.31	0.12	-0.34	-0.10	0.40
Bulk density	0.52*	0.69**	-0.81**	-0.79**	-
Stenvert hardness	-	0.81**	-0.60**	-0.74**	0.52*
Kiya hardness	-	-	-0.78**	-0.78**	0.69**
Endosperm texture	-0.74**	-0.78**	0.80**	-	-0.79**
Dehulling recovery	0.60**	0.78**	-0.78**	-0.81**	0.92**
Water absorption capacity	-0.59**	-0.75**	0.77**	0.83**	-0.92**

Number of cultivars = 20

* Significant at 0.05 level

** Significant at 0.01 level

Grain hardness (Stenvert and Kiya) was positively correlated with bulk density, dehulling recovery and negatively correlated with per cent floaters, endosperm texture and water absorption capacity. Whereas, floaters percentage showed positive association with endosperm texture and water absorption capacity.

4.2 CHEMICAL COMPOSITION

The chemical composition of the whole grains was determined "as is" moisture basis (Table 7). Moisture content of the grains ranged between 8.1 and 11.0 per cent.

Protein content of the cultivars ranged from 6.5 per cent for CSV 8R to 12.7 per cent for P 721 mutant. Much variability among the cultivars was observed in starch and amylose contents of grain. The mean starch content was 67.1 per cent with a higher value of 76.2 per cent for SPV 504 and a lower value of 57.5 per cent for CSV 8R mutant. CSV 8R mutant was found to have a lower amylose content (19.4 per cent) and M 35-1 had higher amylose content (30.9 per cent) among the cultivars.

Total soluble sugars content ranged from 1.1 to 4.5 per cent and the higher value was observed in CSV 8R mutant. Crude fiber content of the cultivars varied between 1.3 and 3.8 per cent with a mean of 1.9 per cent. CSV 11 was found to have lower fat content of 2.8 per cent and CSV 8R mutant had a higher fat content of 9.3 per cent. Except the two mutants, the fat content of the cultivars vary within a

Table 7: Chemical composition of sorghum cultivars

Cultivar	Moisture (%)	Protein (%)	Starch (%)	Amylose (%)	Total soluble sugars (%)	Crude fiber (%)	Fat (%)
M 35-1	11.0	6.7	74.3	30.9	1.3	1.5	3.2
SPV 475	10.1	9.5	67.8	27.0	1.4	1.8	2.9
SPV 504	8.6	7.7	76.2	29.2	1.2	1.4	3.5
SPV 783	8.1	9.7	69.9	27.2	1.3	1.6	3.4
SPV 913	8.7	10.5	69.8	26.9	1.1	1.7	3.1
SPV 980	9.4	10.4	61.7	26.5	1.4	2.0	3.0
SPH 504	8.8	8.6	69.8	28.4	1.1	1.8	3.2
CSH 12R	9.5	9.3	71.4	28.2	1.2	1.6	3.4
CSV 8R	9.5	6.5	71.4	30.5	1.5	1.7	3.6
CSV 8R Mutant	10.6	11.5	57.5	19.4	4.5	3.8	9.3
P 721	8.8	11.5	66.1	25.2	1.7	2.1	3.7
P 721 Mutant	9.2	12.7	58.1	20.4	3.6	3.1	8.2
Nizamabad	8.9	7.8	71.9	27.3	1.5	1.5	4.0
Yellow sorghum	10.4	9.1	62.8	28.2	1.3	1.3	3.0
CSH 1	8.3	11.5	61.5	28.8	1.4	1.8	4.0
CSH 5	9.0	10.2	63.3	29.6	1.3	1.7	3.5
CSH 6	9.1	10.7	65.2	29.6	1.3	1.7	3.8
CSV 10	8.4	12.3	63.5	27.5	1.3	1.5	3.6
CSV 11	8.2	9.1	68.2	29.3	1.1	2.2	2.8
SPH 468	8.2	10.2	71.7	29.2	1.1	1.7	3.1
Minimum	8.1	6.5	57.5	19.4	1.1	1.3	2.8
Maximum	11.0	12.7	76.2	30.9	4.5	3.8	9.3
Mean	**8.9**	**9.8**	**67.1**	**27.5**	**1.6**	**1.9**	**3.9**
SE ±	0.27	0.39	1.17	0.66	0.19	0.13	0.38

Values are mean of two determinations

narrow range of 2.8 to 4.0 per cent.

Table 8 presents the correlation coefficients between physical properties and chemical components of sorghum cultivars. One hundred grain mass and bulk density had positive correlation with starch, amylose and negative correlation with protein content. Endosperm texture, floaters percentage and water absorption capacity showed positive correlation with soluble sugars, fat and negative correlation with starch and amylose contents in the grain.

4.3 STARCH PROPERTIES

4.3.1 Swelling power and solubility

The swelling power and solubility of the isolated starches over a range of temperatures were determined to provide evidence of the associative bonding forces within the granules. Swelling power and solubility of starches isolated from different cultivars are given in Table 9. The swelling power of starches increased with an increase in temperature. Swelling power of starch at 70^{o}C ranged from 1.7 for P 721 mutant to 8.0 for CSV 11. At 80^{o}C, P 721 mutant was found to have lower swelling of 4.3 and SPH 468 had higher swelling of 11.6. The mean swelling power of starch at 90^{o}C was 11.1 with a higher value of 14.1 for SPV 475 and a lower value of 7.0 for CSV 8R mutant.

Solubility of starch at 90^{o}C showed larger variation compared to solubility of starch at 70 and 80^{o}C. Solubility

Table 8: Correlation coefficients (r) between physical properties and chemical components of sorghum cultivars

Physical properties of grain	Grain chemical components				
	Protein	Fat	Starch	Total soluble sugars	Amylose
100-grain mass	-0.54*	-0.38	0.72**	-0.46*	0.48*
Stenvert hardness	0.22	-0.57**	-0.13	-0.50*	0.30
Kiya hardness	-0.13	-0.76**	0.36	-0.73**	0.51*
Bulk density	-0.54*	-0.96**	0.57**	-0.95**	0.87**
Per cent floaters	0.48*	0.80**	-0.46*	0.75**	-0.65**
Endosperm texture	0.19	0.81**	-0.17	0.77**	-0.63**
Water absorption capacity	0.36	0.97**	-0.54*	0.97**	-0.84**

Number of cultivars = 20
* Significant at 0.05 level
** Significant at 0.01 level

Table 9: Swelling power and solubility of isolated starches

Cultivar	Swelling power ($g\ g^{-1}$) at			Solubility (%) at		
	70°C	80°C	90°C	70°C	80°C	90°C
M 35-1	6.4	8.3	13.2	6.6	9.4	16.2
SPV 475	5.1	8.2	14.1	3.8	6.0	16.1
SPV 504	5.1	8.5	12.3	3.5	9.0	16.3
SPV 783	4.2	8.5	11.9	2.4	8.4	20.7
SPV 913	5.5	8.0	9.1	3.9	8.0	15.4
SPV 980	6.6	8.1	10.9	3.5	7.4	15.4
SPH 504	5.9	8.8	11.8	4.4	8.2	16.3
CSH 12R	5.7	9.5	13.4	3.8	9.1	15.0
CSV 8R	6.4	9.4	10.9	6.6	9.0	15.8
CSV 8R Mutant	3.3	5.6	7.0	2.1	4.0	9.9
P 721	5.4	8.2	9.5	3.7	6.2	16.1
P 721 Mutant	1.7	4.3	7.2	1.6	3.5	9.6
Nizamabad	4.2	7.0	10.7	2.9	7.7	14.6
Yellow Sorghum	6.9	8.7	12.7	6.5	9.5	20.8
CSH 1	4.9	7.7	10.1	3.7	10.9	15.6
CSH 5	5.9	9.6	10.7	6.5	11.8	15.2
CSH 6	7.7	11.1	12.3	6.1	13.7	17.3
CSV 10	5.0	10.3	10.1	3.5	12.4	14.1
CSV 11	8.0	8.3	11.9	5.6	9.1	17.3
SPH 468	7.1	11.6	12.2	5.6	13.1	19.8
Minimum	1.7	4.3	7.0	1.6	3.5	9.6
Maximum	8.0	11.6	14.1	6.6	13.7	20.8
Mean	5.6	8.5	11.1	4.3	8.8	15.9
SE ±	0.33	0.37	0.42	0.35	0.61	0.63

Values are mean of three determinations

of starch ranged from 1.6 to 6.6, 3.5 to 13.7 and 9.6 to 20.8 per cent at 70, 80 and 90°C respectively. At all temperatures, P 721 mutant was found to have lower solubility. A higher solubility of 20.8 per cent was observed for yellow sorghum at 90°C.

4.3.2 Pasting characteristics of flour samples

The amylogram results for the flour samples (10 per cent slurry) are given in Table 10. The initial temperature of swelling (pasting temperature) ranged from 69.5 to 80°C with a mean of 72°C. However, the P 721 mutant flour showed an exceptionally high initial temperature of swelling (80°C). The temperature at which peak viscosity was reached for different cultivars varied between 85.8°C and 92.2°C.

Much variability among the cultivars was observed in peak viscosity, viscosity at 95°C, breakdown and set back viscosities of the flour samples (Figure 1). The hot paste consistency of flours at peak viscosity ranged from 150-460 BU. Breakdown viscosity ranged between 105 and 300 BU with a mean of 200 BU. However, the set back viscosity (at 40°C) of the cultivars showed a wide range of 175 to 1030 BU. Among the cultivars M 35-1 had shown higher and CSV 8R mutant had shown lower viscosity at different reference points.

4.3.3 Pasting characteristics of isolated starches

Table 11 presents amylogram results of isolated starches (8 per cent slurry) of 5 selected cultivars with

Table 10: Pasting characteristics of whole meal sorghum flours

Cultivar	Pasting temperature (^{o}C)		Peak viscosity (BU)	Hot paste viscosity at $95^{o}C$ (BU)	Breakdown viscosity (BU)	Paste viscosity (BU) at	
	Initial	Final				$50^{o}C$	$40^{o}C$
M 35-1	70.3	86.5	460	380	300	815	1030
SPV 475	72.8	90.5	265	255	220	585	720
SPV 504	70.5	85.8	265	190	160	465	640
SPV 783	69.5	86.0	185	155	140	360	555
SPV 913	70.0	91.0	255	245	190	500	590
SPV 980	72.5	91.0	205	195	185	480	580
SPH 504	70.0	88.5	390	330	255	715	855
CSH 12R	70.8	88.0	380	310	240	655	800
CSV 8R	71.0	86.5	335	295	240	625	880
CSV 8R Mutant	78.5	91.0	150	140	105	200	175
P 721	75.5	90.0	270	240	190	505	560
P 721 Mutant	80.0	92.2	180	165	130	315	285
Nizamabad	71.3	88.0	380	320	245	680	820
Yellow Sorghum	70.5	86.0	340	270	225	590	740
CSH 1	71.0	89.0	295	235	200	615	695
CSH 5	71.3	86.8	270	195	165	460	550
CSH 6	70.8	88.0	305	255	215	630	745
CSV 10	71.5	86.0	265	200	170	560	615
CSV 11	71.0	88.5	295	245	205	600	695
SPH 468	71.0	88.5	360	290	225	655	760
Minimum	69.5	85.8	150	140	105	200	175
Maximum	80.0	92.2	460	380	300	815	1030
Mean	**72.0**	**88.4**	**293**	**246**	**200**	**551**	**665**
SE $\pm$	0.63	0.45	17.7	14.2	10.5	32.3	43.5

BU: Brabender Units
Values are mean of duplicate determinations

Fig.1. Pasting properties of sorghum flours

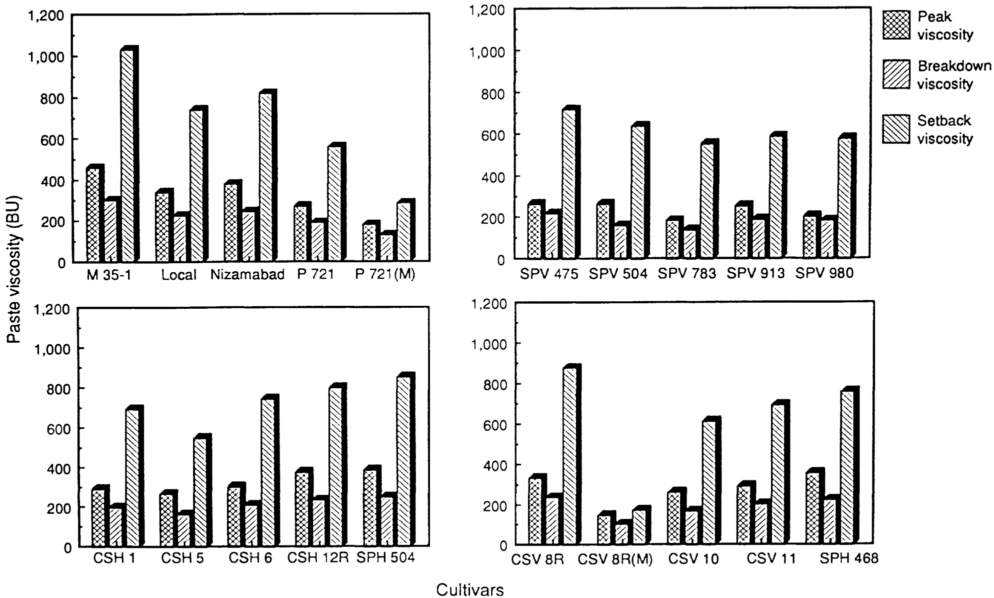


Table 11: Pasting characteristics of isolated sorghum starches

Cultivar	Pasting temperature (^{o}C)		Peak (BU)	Hot paste at 95^{o}C (BU)	Breakdown (BU)	Paste viscosity	
	Initial	Final				50^{o}C	40^{o}C
CSV 8R	71.0	84.2	625	490	430	1090	1420
Yellow Sorghum	70.5	83.0	725	540	395	1005	1215
SPV 913	69.0	89.0	695	580	380	1015	1100
P 721	73.0	88.0	730	505	335	975	1040
CSV 8R Mutant	82.5	91.0	600	540	415	1015	1260
Minimum	69.0	83.0	600	490	335	975	1040
Maximum	82.5	91.0	730	580	430	1090	1420
Mean	**73.2**	**87.0**	**675**	**531**	**391**	**1020**	**1207**
SE ±	2.41	1.50	26.5	15.7	16.4	19.0	66.2

Values are mean of duplicate determinations
BU: Brabender units

good and poor popping quality. The initial swelling temperature of starches ranged from 69.0 to 82.5^{o}C. Among the cultivars studied, CSV 8R mutant starch displayed an exceptionally high initial temperature (82.5^{o}C) of swelling. P 721 starch showed higher peak viscosity. Whereas, SPV 913 starch had high paste viscosity at 95^{o}C. Higher values for breakdown viscosity, setback viscosity at 50 and 40^{o}C were observed for CSV 8R starch than other cultivars.

4.4 POPPING QUALITY

Grain samples of 20 sorghum cultivars were popped at 16 per cent moisture level and 240^{o}C temperature for 2 minutes. Local variety of maize was also popped under the same conditions (Plates 1, 2, 3, 4 and 5). Sorghum pops were evaluated for various physicochemical characteristics, organoleptic qualities and *in vitro* starch and protein digestibility.

4.4.1 Physicochemical properties of pops

Table 12 gives the physical properties of pops from 20 sorghum cultivars. There were significant genotypic differences in the popping quality of sorghum cultivars. Total popped volume of 50 g sample varied between 115 and 597 ml with a mean of 366 ml. Among the cultivars CSH 6 had the higher popped volume (597 ml) followed by yellow sorghum (593 ml), CSV 11 (580 ml), CSV 8R (547 ml), SPH 504 (507 ml) and SPH 468 (501 ml). P 721 mutant had the lower popped volume (115 ml).

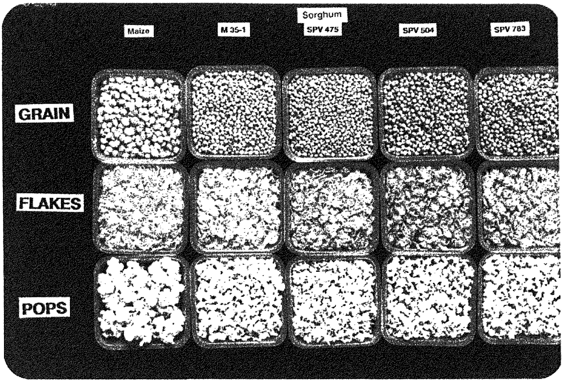


Plate 1. Comparison of flakes and pops of sorghum cultivars- M 35-1, SPV 475, SPV 504, SPV 783, and maize (local).

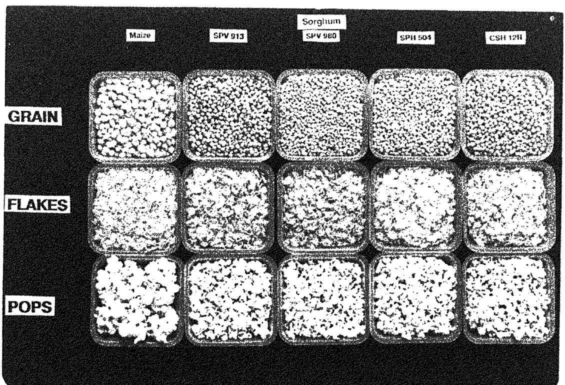


Plate 2. Comparison of flakes and pops of sorghum cultivars - SPV 913, SPV 980, SPH 504, CSH 12R, and maize (local).

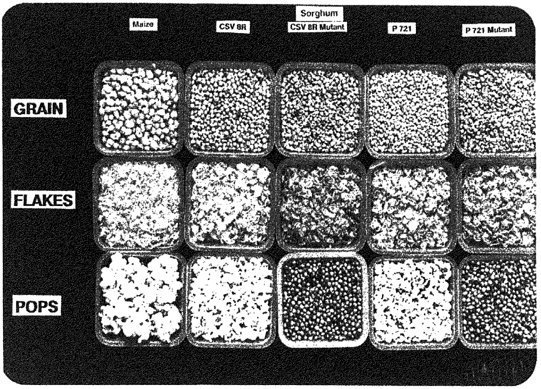


Plate 3. Comparison of flakes and pops of sorghum cultivars - CSV 8R, CSV 8R mutant, P 721, P 721 mutant and maize (local).

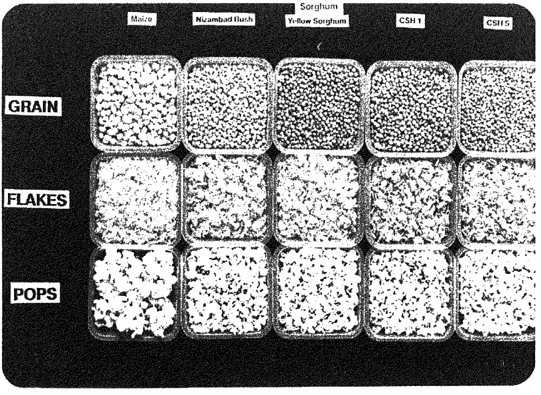


Plate 4. Comparison of flakes and pops of sorghum cultivars - Nizamabad, Yellow sorghum, CSH 1, CSH 5 and maize (local).

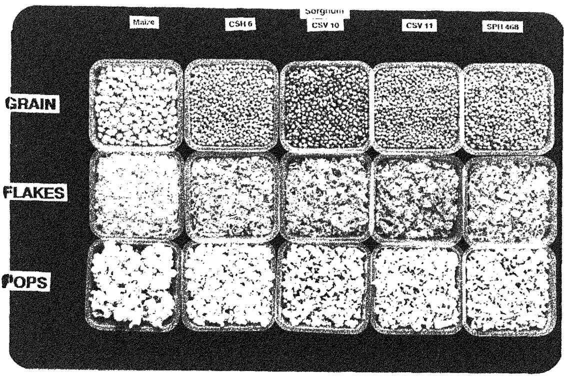


Plate 5. Comparison of flakes and pops of sorghum cultivars - CSH 6, CSV 10, CSV 11, SPH 468 and maize (local).

Table 12: Physical properties of sorghum pops

Cultivar	Popped volume (ml)	Bulk density ($g\ L^{-1}$)	Popping per cent	Expansion ratio	Expansion volume ($ml\ g^{-1}$)	Instron values ($kg\ sq.cm^{-1}$)
M 35-1	393	127	85	6.7	7.9	83.2
SPV 475	415	120	68	6.9	8.3	100.0
SPV 504	288	174	77	4.8	5.8	78.8
SPV 783	297	168	78	5.0	5.9	86.0
SPV 913	237	211	58	4.0	4.7	66.0
SPV 980	337	148	68	5.8	6.7	78.0
SPH 504	507	99	84	8.7	10.1	105.2
CSH 12R	340	147	85	5.7	6.8	84.0
CSV 8R	547	91	90	9.1	10.9	98.0
CSV 8R Mutant	122	410	0	1.7	2.4	*
P 721	188	266	31	3.1	3.8	68.7
P 721 Mutant	115	435	0	1.6	2.3	*
Nizamabad	333	150	80	5.6	6.7	67.3
Yellow Sorghum	593	84	91	10.2	11.9	82.0
CSH 1	305	164	75	4.7	6.1	56.0
CSH 5	423	118	73	6.3	8.5	69.2
CSH 6	597	84	90	9.2	11.9	82.4
CSV 10	208	240	55	3.0	4.2	50.0
CSV 11	580	86	85	8.9	11.6	70.0
SPH 468	501	100	90	7.5	10.0	73.2
Minimum	115	84	0	1.6	2.3	50.0
Maximum	597	435	91	10.2	11.9	105.2
Mean	**366**	**171**	**68**	**5.9**	**7.3**	**77.7**
SE ±	34.1	22.4	6.2	0.56	0.68	3.41

Values are mean of three determinations
* Not suitable for crispness measurement

Popping per cent of the cultivars showed wide variation from zero per cent for CSV 8R mutant and P 721 mutant to 91 per cent for yellow sorghum (local variety) with a mean of 67 per cent. Among the cultivars higher expansion volume (11.9 ml g^{-1}) was observed in yellow sorghum and CSH 6. Yellow sorghum also had shown higher expansion ratio. A low expansion volume (2.3 ml g^{-1}) and expansion ratio (1.6) were observed in P 721 mutant. Bulk density of pops ranged from 84 g L^{-1} (CSH 6) to 438 g L^{-1} (P 721 mutant) with a mean of 171 g L^{-1}. Instron values showed the maximum force per gram of pops in SPH 504 cultivar (105.2 kg sq. cm^{-1}) and minimum force was in CSV 10 pops (50.0 kg sq. cm^{-1}).

Chemical composition of pops from some cultivars having poor and good popping quality is presented in Table 13. Protein, starch, fat and crude fiber contents were higher in popped grain as compared to whole grain. Whereas, the moisture content was reduced on popping. Good popping sorghums have relatively higher starch and lower protein contents compared to poor popping sorghums.

4.4.2 Relationship between grain characteristics and physical properties of pops

Correlation coefficients determined between popping quality and physicochemical characters of grain, swelling power and solubility of starch and pasting properties of flour revealed the following facts (Tables 14, 15, 16 and 17).

Table 13: Chemical composition of sorghum pops

Cultivar	Protein (%)	Starch (%)	Fat (%)	Crude fiber (%)	Moisture (%)
Good Popping Quality:					
CSV 8R	7.1	77.2	3.7	2.0	7.1
Yellow Sorghum	10.5	75.5	3.7	1.7	6.4
CSH 6	11.4	77.2	3.8	2.1	7.1
Poor Popping Quality:					
SPV 913	11.1	72.0	3.3	1.8	6.5
P 721	10.6	71.9	3.8	2.3	6.3
CSV 10	13.2	72.1	3.7	1.7	6.6
Minimum	7.1	71.9	3.3	1.7	6.3
Maximum	13.2	77.2	3.8	2.3	7.1
Mean	**10.7**	**74.3**	**3.7**	**1.9**	**6.7**
SE ±	0.81	1.07	0.08	0.10	0.14

Values are mean of two determinations

Table 14: Correlation coefficients (r) between physicochemical properties and popping quality of sorghum cultivars

Physicochemical properties of grain	Physical properties of pops			
	Popped volume	Popping per cent	Bulk density	Expansion ratio
100-grain mass	0.04	0.51*	-0.32	0.10
Kernel thickness	0.23	0.63**	0.47*	0.26
Bulk density	0.68**	0.90**	-0.92**	0.71**
Stenvert hardness	0.38	0.33	-0.46*	0.35
Kiya hardness	0.43	0.53*	-0.60**	0.42
Per cent floaters	-0.56**	-0.72**	0.74**	-0.61**
Endosperm texture	-0.46*	-0.62**	0.69**	-0.48*
Protein	-0.54*	-0.66**	0.62**	-0.60**
Fat	-0.60**	-0.84**	0.87**	-0.62**
Starch	0.32	0.63**	-0.55*	0.37
Amylose	0.73**	0.93**	-0.91**	0.73**
Total soluble sugars	-0.58**	-0.86**	0.86**	-0.60**

Number of cultivars = 20
* Significant at 0.05 level
** Significant at 0.01 level

Table 15: Correlation coefficients (r) between swelling and solubility of isolated starches and physical properties of pops

Swelling & solubility of starches	Physical properties of pops			
	Popped volume	Bulk density	Popping per cent	Expansion ratio
Swelling power at 70°C	0.83**	-0.83**	0.75**	0.81**
Swelling power at 80°C	0.61**	-0.72**	0.72**	0.57**
Swelling power at 90°C	0.69**	-0.83**	0.83**	0.72**
Solubility at 70°C	0.82**	-0.74**	0.67**	0.80**
Solubility at 80°C	0.56**	-0.65**	0.70**	0.49*
Solubility at 90°C	0.66**	-0.77**	0.77**	0.68**

Number of cultivars = 20
* Significant at 0.05 level
** Significant at 0.01 level

Table 16: Correlation coefficients (r) between pasting characterstics of flour and physical properties of sorghum pops

Pasting characteristics of flour	Physical properties of pops			
	Popped Volume	Bulk Density	Popping Per cent	Expansion ratio
Pasting temparature	-0.61**	0.87**	-0.92**	-0.64**
Peak viscosity	0.57**	-0.64**	0.68**	0.60**
Viscosity at 95°C	0.54*	-0.60**	0.61**	0.58**
Breakdown viscosity	0.62**	-0.70**	0.70**	0.66**
paste viscosity at 50°C	0.62**	-0.74**	0.76**	0.65**
Set back viscosity at 40°C	0.67**	-0.82**	0.85**	0.71**

Number of cultivars = 20
*   Significant at 0.05 level
** Significant at 0.01 level

Table 17: Correlation coefficients (r) between Instron values, physical and sensory properties of pops

Characteristics		(r)
Instron values vs (Force per gram pops)	Popped volume	0.50*
	Expansion ratio	0.59**
	Popping per cent	0.43
	Bulk density	-0.56*
	Sensory texture	0.70**
	Protein	-0.60**

Number of cultivars = 18
* Significant at 0.05 level
** Significant at 0.01 level

One hundred grain mass did not show significant correlation with the popping quality parameters except with the popping per cent (r = 0.51*).

Kernel thickness had significant positive correlation (r = 0.63**) with popping per cent and negative correlation (r = -0.47*) with bulk density of pops.

Stenvert hardness showed negative correlation (r = -0.46*) with the bulk density of pops. Breaking strength of grains (kiya hardness) showed positive correlation (r = 0.53*) with popping per cent and negative correlation (r = -0.60**) with bulk density of pops.

Floaters per cent and endosperm texture had negative correlation with the popped volume, expansion ratio, popping per cent and significant positive correlation with the bulk density of pops.

Bulk density of grain was positively correlated (Figs 2 and 3) with the popped volume (r = 0.68**), expansion ratio (r = 0.71**) and popping per cent (r = 0.90**).

Protein, fat and total soluble sugars content of grain showed significant negative relationship with the popped volume, expansion ratio, popping per cent and positive relationship with the bulk density of pops.

Fig.2. Relationship between bulk density of grain and expansion volume of pops

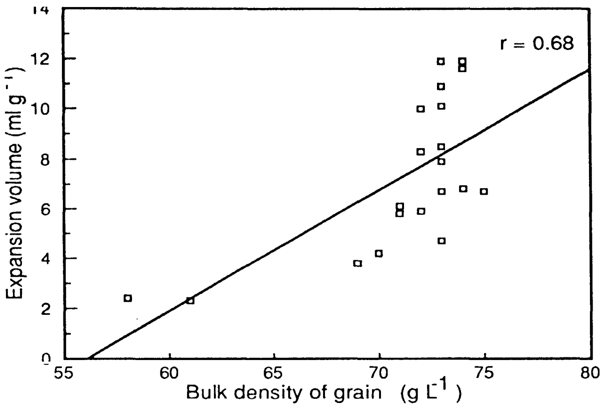
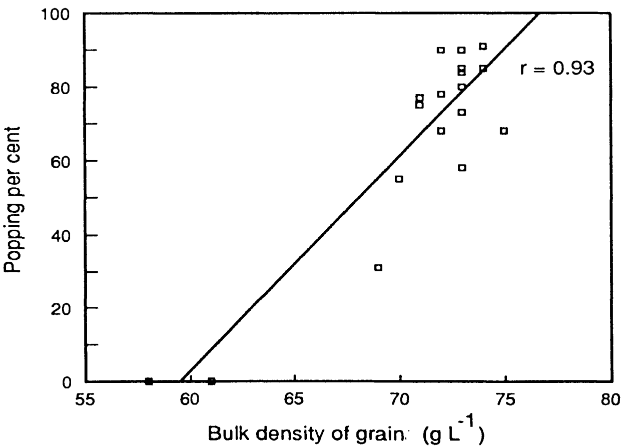


Fig.3. Relationship between bulk density of grain and popping per cent



Starch content of grain was positively correlated (r = 0.63**) with the popping per cent and negatively correlated with the bulk density of pops (r = -0.55*).

Amylose content of grain showed highly significant positive correlation (Figs 4 and 5) with the popping per cent (r = 0.93**), popped volume (r = 0.73**), expansion ratio (r = 0.73**) and negative relationship with the bulk density of pops.

Swelling power and solubility of starch at different temperatures (70, 80 and 90°C) showed significant positive correlation with the popped volume, expansion ratio, popping per cent (Figures 6 and 7).

The initial pasting temperature of flour had significant negative correlation with the popped volume (r = -0.61**), expansion ratio (r = -0.64**), popping per cent (r = -0.92**) and significant positive correlation (r = 0.87**) with the bulk density of pops.

aste viscosity of flour at different reference points (peak viscosity, viscosity at 95°C, breakdown viscosity, paste viscosity at 50° and 40°C) showed significant positive relationship with popped volume, expansion ratio, popping per cent and negative correlation with the bulk density of pops.

Fig.4. Relationship between amylose content of grain and expansion volume of pops

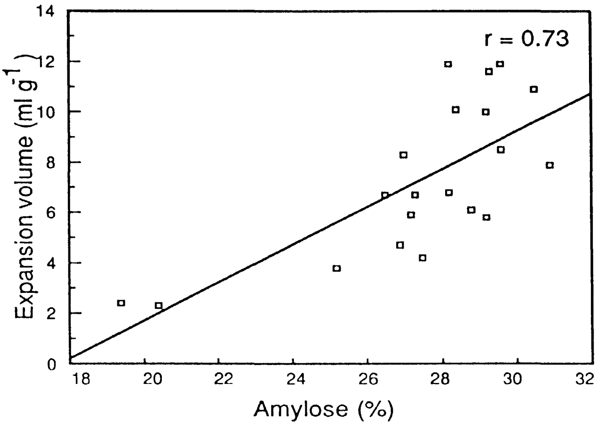


Fig.5. Relationship between amylose content of grain and popping per cent

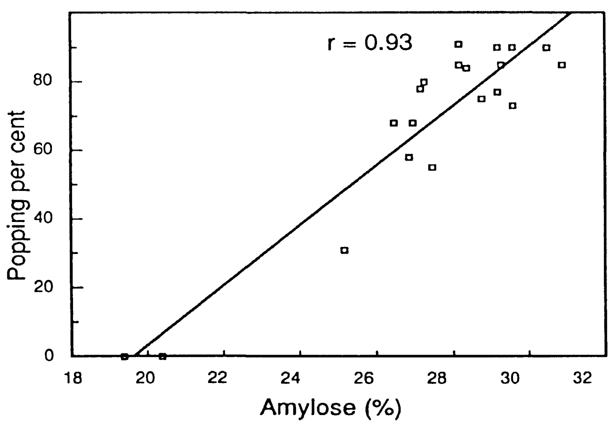


Fig.6. Relationship between swelling power of starch and expansion volume of pops

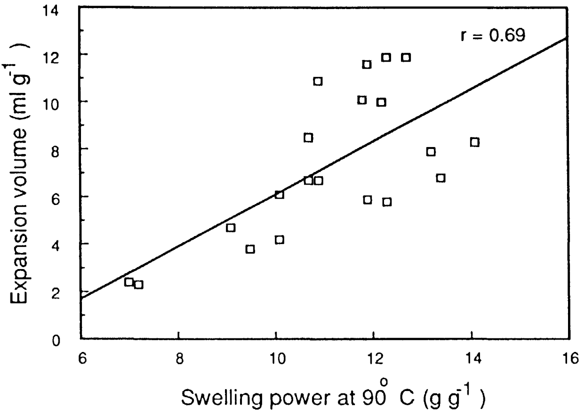
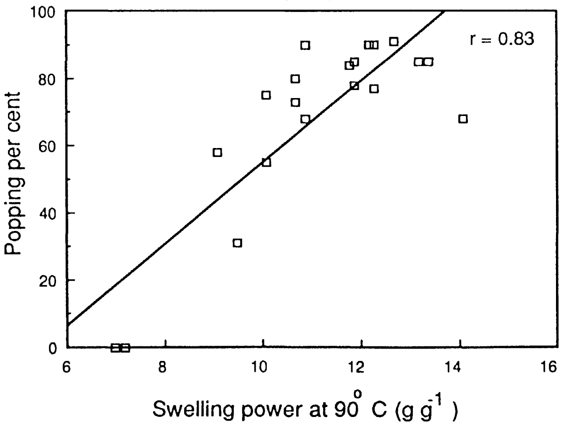


Fig.7. Relationship between swelling power of starch and popping per cent



- Force per gram of pops using kramer shear cell (in Instron Universal Testing Machine) had positive correlation with popped volume (r = 0.50*), expansion ratio of pops (r = 0.59**) and strong positive correlation with the sensory texture (r = 0.70**).

To study the relative contribution of the grain characteristics to physical properties of pops, stepwise multiple regression was adopted by considering the popping quality characters as dependent variables and the grain characteristics as independent variables (Table 18).

Among the physicochemical characteristics studied, the starch properties such as solubility of starch at 80°C, pasting temperature and paste viscosity of flour at 40 and 50°C together showed significant relationship (R^2 = 0.95) with the percentage of popping. Kernel thickness along with the swelling power of starch at 90°C, solubility of starch at 70°C and pasting temperature of flour showed significant relationship (R^2 = 0.82) with popped volume. The same parameters influenced the bulk density of pops (R^2 = 0.94). Whereas, 100-grain mass along with swelling power of starch at 70°C, paste viscosity of flour at 40 and 50°C showed significant association (R^2 = 0.84) with the expansion ratio of pops.

4.4.3 Organoleptic Qualities of Sorghum Pops

Table 19 presents the mean scores for different organoleptic qualities (sensory properties) of sorghum pops.

Table 18: Stepwise multiple regression coefficients for the physical properties of pops and grain characteristics.

	Intercept	Regression coefficient	R^2	Prob > F (Level of significance)
Popping per cent:				
Solubility at 80°C	243.49	2.53 (0.89)	0.95	0.012
Paste viscosity at 50°C		-0.10 (0.04)		0.028
Cold paste viscosity at 40°C		0.14 (0.03)		0.001
Pasting temparature		-3.27 (1.20)		0.016
Popped volume:				
Kernel thickness	1183.22	-144.00 (66.30)	0.82	0.046
Swelling power at 90°C		28.59 (13.03)		0.044
Solubility at 70°C		56.56 (12.93)		< 0.001
Pasting temparature		-13.75 (10.31)		0.203
Bulk density of pops:				
Kernel thickness	-1.28	0.07 (0.03)	0.94	0.015
Swelling power at 90°C		-0.02 (0.01)		0.001
Solubility at 70°C		-0.02 (0.01)		0.002
Pasting temparature		0.02 (0.001)		< 0.001
Expansion ratio:				
100-grain mass	1.97	-1.26 (0.52)	0.84	0.029
Swelling power at 70°C		0.66 (0.26)		0.021
Paste viscosity at 50°C		-0.02 (0.01)		0.013
Cold paste viscosity at 40°C		0.02 (0.01)		0.002
Expansion volume:				
Kernel thickness	23.03	-2.84 (1.31)	0.82	0.047
Swelling power at 90°C		0.58 (0.26)		0.041
Solubility at 70°C		1.14 (0.26)		< 0.001
Pasting temparature		-0.27 (0.21)		0.208

The values in parenthesis indicate standard error (±)

Table 19: Organoleptic qualities of sorghum pops

Cultivar	Color and appearance	Texture	Flavor	Accepta-bility	Mean scores
M 35-1	4.7	4.6	4.1	4.1	4.4
SPV 475	3.9	4.4	3.8	3.8	4.0
SPV 504	4.1	4.1	3.3	3.4	3.8
SPV 783	4.2	4.2	3.3	3.4	3.8
SPV 913	4.1	4.2	4.1	3.7	4.0
SPV 980	3.9	4.7	4.0	4.0	4.2
SPH 504	4.6	4.8	4.1	4.2	4.4
CSH 12R	4.6	4.3	4.1	4.3	4.4
CSV 8R	4.7	4.7	4.3	4.6	4.6
CSV 8R Mutant	1.3	3.4	2.2	1.8	2.2
P 721	4.0	4.2	3.6	3.6	3.8
P 721 Mutant	1.1	3.4	2.0	1.6	2.1
Nizamabad	4.7	4.1	3.8	4.0	4.2
Yellow Sorghum	4.6	4.6	3.9	4.1	4.3
CSH 1	4.6	4.1	3.6	3.8	4.0
CSH 5	4.3	4.6	3.7	3.6	4.1
CSH 6	4.8	4.7	4.2	4.4	4.6
CSV 10	3.1	3.1	3.1	2.2	2.9
CSV 11	4.6	4.6	4.0	4.0	4.3
SPH 468	4.6	4.3	4.0	4.2	4.3
Minimum	1.1	3.1	2.0	1.6	2.1
Maximum	4.8	4.8	4.3	4.6	4.6
Mean	4.0	4.3	3.7	3.6	3.9
SE ±	0.24	0.11	0.14	0.19	0.16

Values are mean scores of nine panelists
Organoleptic properties are rated on hedonic scale of 1-5
(5 is excellent; 1 is unacceptable)

Table 19a: Analysis of variance of cultivars for popping quality

Source of variation	Mean square	d.f	F	P
Color and appearance	9.676	19	33.341	< 0.001
Texture	1.837	19	4.572	< 0.001
Flavour	3.491	19	8.340	< 0.001
Acceptability	6.361	19	19.577	< 0.001
Mean scores	4.501	19	32.629	< 0.001

Color and appearance scores of pops ranged from 1.1 (P 721 mutant) to 4.8 (CSH 6). Mean rating for texture was 4.3 with higher rating (4.8) for SPH 504 and lower rating (3.1) for CSV 10. Flavor ratings ranged from 2.0 (P 721 mutant) to 4.3 (CSV 8R) with a mean of 3.7. Acceptability scores ranged between 1.6 (P 721 mutant) and 4.6 (CSV 8R) with a mean of 3.6. The overall evaluation of the pops considering all the sensory qualities scored maximum for CSV 8R and CSH 6 pops. P 721 mutant pops were rated as poor. Analysis of variance showed significant differences among the cultivars for the sensory properties of pops.

4.4.4 Relationship between sensory properties of pops and physicochemical characteristics

The association between physicochemical characteristics of grain, physical properties of pops and the taste panel scores of pops are given in Tables 20 and 21.

Color and appearance, flavor, and acceptability of pops showed positive correlation with the breaking strength and a strong negative correlation with the per cent floaters and endosperm texture. A highly significant correlation was observed between sensory properties of pops and bulk density of grain.

Sensory properties of pops were negatively correlated with protein, fat, soluble sugars and positively correlated with starch and amylose content in the grain. Popped volume, popping per cent and expansion ratio had strong positive

Table 20: Correlation coefficients (r) between physicochemical characteristics and sensory properties of pops

Physicochemical characteristics of grain	Sensory properties of pops			
	Color and appearance	Texture	Flavor	Accepta-bility
Bulk density	0.92**	0.78**	0.90**	0.87**
Kernel thickness	0.59**	0.27	0.43	0.45*
Stenvert hardness	0.38	0.31	0.39	0.32
Kiya hardness	0.59**	0.41	0.63**	0.50*
Endosperm texture	-0.63**	-0.54*	-0.63**	-0.55*
Per cent floaters	-0.71**	-0.68**	-0.70**	-0.70**
Water absorption capacity	-0.86**	-0.64**	-0.81**	-0.76**
Protein	-0.65**	-0.68**	-0.60**	-0.69**
Fat	-0.87**	-0.68**	-0.84**	-0.79**
Starch	0.66**	0.49*	0.61**	0.62**
Amylose	0.91**	0.68**	0.80**	0.78**
Total soluble sugars	-0.89**	-0.64**	-0.83**	-0.77**

Number of cultivars = 20
*   Significant at 0.05 level
** Significant at 0.01 level

Table 21: Correlations coefficients (r) between physical properties and sensory properties of pops

Physical properties of pops	Sensory properties of pops			
	Color and appearance	Texture	flavor	Acceptabi-lity
Popped volume	0.74**	0.68**	0.67**	0.70**
Expansion ratio	0.76**	0.74**	0.71**	0.75**
Expansion volume	0.74**	0.68**	0.67**	0.70**
Popping per cent	0.93**	0.72**	0.82**	0.83**
Bulk density	-0.93**	-0.80**	-0.86**	-0.86**

Number of cultivars = 20
*   Significant at 0.05 level
** Significant at 0.01 level

correlation with the sensory properties of pops.

Table 22 shows the results of stepwise multiple regression analysis between sensory qualities of pops and grain characteristics. Color and appearance of pops had shown strong relationship (R^2 = 0.93) with the bulk density of grain along with pasting temperature, paste viscosity of flour at 95°C and the solubility of starch at 70°C. Texture of pops showed significant association with breaking strength and water absorption capacity of grain along with the swelling power of starch at 70°C and solubility of starch at 80°C (R^2 = 0.83).

Whereas, the bulk density of grain, swelling power of starch at 70°C, breakdown viscosity and paste viscosity of flour at 50°C jointly contribute to the variation in flavor (R^2 = 0.89) and acceptability (R^2 = 0.88) of pops.

4.5 FLAKING QUALITY

For the preparation of sorghum flakes the dehulled grains were soaked in water, pressure cooked, conditioned, flaked and dried. The flakes were prepared from 20 sorghum cultivars and local variety of maize (Plates 1, 2, 3, 4 and 5). Sorghum flakes were evaluated for their physicochemical characteristics, organoleptic qualities and *in vitro* starch and protein digestibility.

Table 22: Stepwise multiple regression coefficients for the sensory qualities of pops and grain characteristics.

	Intercept	Regression coefficient	R^2	Prob > F (Level of significance)
Color and appearance:				
Bulk density of grain	3.29	13.38 (5.20)	0.93	0.021
Solubility at 70°C		0.10 (0.06)		0.112
Hot paste viscosity at 95°C		0.003(0.001)		0.039
Pasting temparature		-0.14 (0.06)		0.031
Texture:				
Breaking strength	6.70	-0.19 (0.05)	0.83	0.002
Water absorption capacity of grain		-0.04 (0.01)		< 0.001
Swelling power at 70°C		0.27 (0.05)		< 0.001
Solubility at 80°C		-0.12 (0.03)		< 0.001
Flavor:				
Bulk density of grain	-6.55	13.00 (2.76)	0.89	< 0.001
Swelling power at 70°C		0.08 (0.05)		0.113
Breakdown viscosity		0.01 (0.004)		0.003
Paste viscosity at 50°C		-0.004(0.002)		0.019
Acceptibility:				
Bulk density of grain	-9.86	16.99 (3.73)	0.88	< 0.001
Swelling power at 70°C		0.10 (0.07)		0.146
Breakdown viscosity		0.03 (0.01)		< 0.001
Paste viscosity at 50°C		-0.01 (0.002)		0.003

The values in parenthesis indicate standard error (±)

4.5.1 Physicochemical characteristics of sorghum flakes

Results of the physical properties of flakes is presented in Table 23. The mean bulk density of flakes was 293 g L^{-1}. SPV 980 cultivar produced flakes with higher bulk density (351 g L^{-1}) and P 721 mutant produced flakes with lower bulk density (175 g L^{-1}). Among the non mutant cultivars, Nizamabad, M 35-1, Yellow sorghum, CSH 6 and SPH 468 produced flakes with lower bulk density. The property of producing lower bulk density is the criteria for good flaking quality. Flaking recovery values did not show much variation among the cultivars except for CSV 8R mutant and P 721 mutant. The two mutants, however, had low flaking recovery compared to other cultivars. The mean water absorption capacity of sorghum flakes was 146 g $100g^{-1}$, with higher value for CSV 8R mutant (178 g $100g^{-1}$) and a lower value for CSH 1 (124 g $100g^{-1}$).

Table 24 gives the chemical composition of sorghum flakes made from cultivars with poor and good flaking quality. The protein, fat, crude fiber and moisture content of flakes were lowered as compared to whole grain. Whereas, the starch content was increased.

4.5.2 Relationship between physical properties of flakes and grain characteristics

Results of correlation coefficients between physical properties of flakes and physicochemical properties of grain are presented in Table 25.

Table 23: Physical properties of sorghum flakes

Cultivar	Volume of 100 g flakes (ml)	Bulk density (g L^{-1})	Flaking recovery (%)	Water absorption capacity (g $100g^{-1}$)
M 35-1	350	286	96	172
SPV 475	318	314	96	125
SPV 504	307	329	97	150
SPV 783	328	305	95	143
SPV 913	323	310	96	133
SPV 980	285	351	97	125
SPH 504	317	315	98	135
CSH 12R	325	308	96	162
CSV 8R	312	321	98	155
CSV 8R Mutant	560	179	87	178
P 721	323	310	95	124
P 721 Mutant	570	175	84	177
Nizamabad	368	272	96	143
Yellow Sorghum	348	287	95	138
CSH 1	325	308	97	124
CSH 5	328	305	97	164
CSH 6	347	288	98	141
CSV 10	328	305	96	146
CSV 11	332	301	97	143
SPH 468	343	292	98	139
Minimum	285	175	84	124
Maximum	570	351	98	178
Mean	**352**	**293**	**95**	**146**
SE ±	16.8	9.6	0.9	3.9

Values are mean of three determinations

Table 24: Chemical composition of sorghum flakes

Cultivar	Protein (%)	Starch (%)	Fat (%)	Crude fiber (%)	Moisture (%)
Good flaking quality:					
M 35-1	5.9	80.0	2.1	0.5	8.2
Nizamabad	7.0	76.2	2.1	0.5	8.2
Yellow sorghum	8.9	75.2	2.0	0.4	8.2
CSH 6	9.9	77.6	2.1	0.6	8.8
SPH 468	9.3	76.2	1.8	0.5	8.4
Poor flaking quality:					
SPV 504	7.3	81.0	1.9	0.4	8.0
SPV 980	10.3	73.5	2.1	0.7	8.4
CSV 8R	5.8	76.9	1.8	0.5	8.8
Minimum	5.8	73.5	1.8	0.4	8.0
Maximum	10.3	81.0	2.1	0.7	8.8
Mean	**8.1**	**77.1**	**2.0**	**0.5**	**8.4**
SE ±	0.63	0.87	0.05	0.04	0.10

Values are mean of duplicate determinations

Table 25: Correlation coefficients (r) between physicochemical properties of grain and physical properties of flakes

Grain Characteristics	Physical properties of flakes			
	Volume of 100 g flakes	Bulk density	Flaking recovery	Water absorption capacity
100-grain mass	-0.39	0.34	0.40	-0.01
Bulk density	-0.91**	0.86**	0.92**	-0.53*
Kernel thickness	-0.38	0.29	0.47*	0.11
Stenvert hardness	-0.55*	0.54*	0.49*	-0.72**
Kiya hardness	-0.74**	0.73**	0.69**	-0.72**
Endosperm texture	0.83**	-0.83**	-0.76**	0.74**
Per cent floaters	0.78**	-0.78**	-0.69**	0.54*
Water absorption capacity	0.96**	-0.91**	-0.93**	0.69**
Protein	0.42	-0.39	-0.48*	-0.08
Fat	0.96**	-0.91**	-0.93**	0.62**
Starch	-0.56**	0.51*	0.60**	-0.09*
Amylose	-0.83**	0.76**	0.92**	-0.30
Total soluble sugars	0.94**	-0.89**	-0.94**	0.58**

Number of cultivars = 20

* Significant at 0.05 level

** Significant at 0.01 level

Bulk density of flakes showed significant positive correlation with stenvert hardness (r = 0.54*), kiya hardness (r = 0.73**) and bulk density of grain (r = 0.86**). A significant negative correlation (Figs 8 and 9) was observed for bulk density of flakes with endosperm texture (r = -0.83**), water absorption capacity of grains (r = -0.91**) and per cent floaters (r = -0.78**).

Bulk density of flakes was negatively correlated with fat (r = -0.91**), total soluble sugars (r = -0.89**), and positively correlated with starch (r = 0.51*) and amylose (r = 0.76**) content in the grain.

Water absorption capacity of flakes had significant negative correlation with stenvert hardness (r = -0.72**) kiya hardness (r = -0.72**), and bulk density of grain (r = -0.53*). A significant positive correlation was obtained for water absorption capacity of flakes with fat and soluble sugars content, per cent floaters, endosperm texture and water absorption capacity of grain.

Table 26 gives the correlation coefficients of physical properties of flakes with swelling power and solubility of isolated starches. Swelling power and solubility of starch at different temperatures (70^{o}, 80^{o} and $90^{o}C$) had positive relationship with the bulk density of flakes. Water absorption capacity of flakes was inversely related (r = -0.55*) with the solubility of starch at $90^{o}C$.

Fig.8. Relationship between endosperm texture and bulk density of flakes

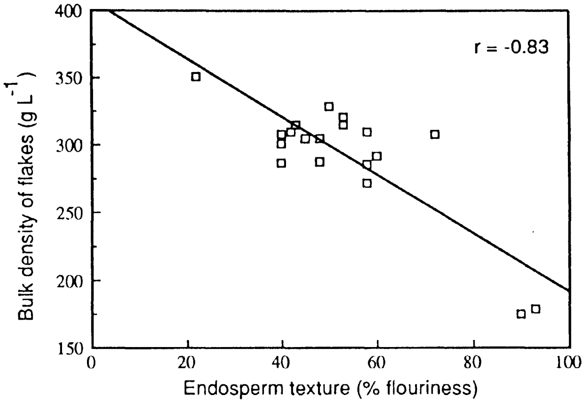
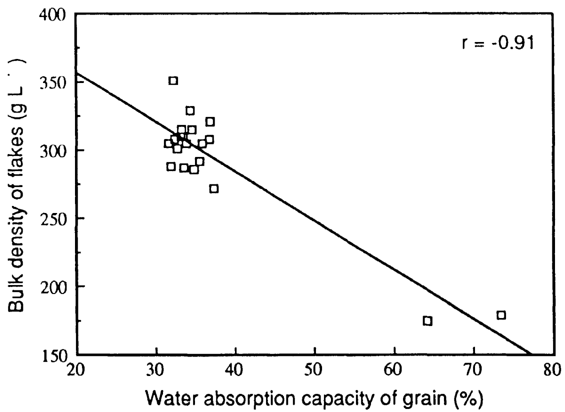


Fig.9. Relationship between water absorption capacity of grain and bulk density of flakes



Results of simple correlations between pasting properties of flour and physical properties of flakes are given in Table 27. Pasting temperature showed significant negative correlation (r = -0.78**) with the bulk density of flakes. Whereas, cold paste viscosity had significant positive relationship with the bulk density of flakes (r = 0.50*, r = 0.60** for cold paste viscosity at 50^{o}C and 40^{o}C respectively)

Table 28 shows the stepwise multiple regression between physical properties of flakes and grain characteristics. Floaters percentage, bulk density of grain, solubility of starch at 90^{o}C and peak viscosity of flour together showed significant relationship (R^2 = 0.94) with the bulk density of flakes. Whereas, the water absorption capacity of flakes showed weak association (R^2 = 0.76) with the combined effect of stenvert hardness, endosperm texture, solubility of starch at 70^{o}C and hot paste viscosity of flour at 95^{o}C.

4.5.3 Organoleptic qualities of flakes

Table 29 gives the mean scores for sensory qualities of sorghum flakes. Among the cultivars, yellow sorghum flakes rated high (4.7) for color and appearance and CSV 8R mutant flakes rated low (2.2). Texture ratings ranged from 3.0 (SPV 504) to 4.7 (CSV 8R mutant) with a mean of 3.5. Texture retention of flakes was studied by soaking the flakes in milk. A higher score for the texture of flakes in milk was obtained for CSV 8R mutant (4.8) and a lower score of 3.3

Table 26: Correlation coefficients (r) between swelling power, solubility of isolated starches and physical properties of flakes

Swelling and solubility of starches	Physical properties of flakes: Volume of 100 g flakes	Bulk density	Flaking recovery	Water absorption capacity
Swelling power at 70°C	-0.67**	0.63**	0.77**	-0.38
Swelling power at 80°C	-0.69**	0.64**	0.79**	-0.32
Swelling power at 90°C	-0.68**	0.62**	0.70**	-0.29
Solubility at 70°C	-0.46*	0.39	0.60**	-0.03
Solubility at 80°C	-0.56**	0.48*	0.71**	-0.20
Solubility at 90°C	-0.69**	0.62**	0.70**	-0.53*

Number of cultivars = 20
* Significant at 0.05 level
** Significant at 0.01 level

Table 27: Correlation coefficients (r) between pasting properties of flour and physical properties of flakes

Pasting properties of flour	Physical properties of flakes: Bulk volume	Bulk density	Flaking recovery	Water absorption capacity
Pasting temparature	0.84**	-0.78**	-0.89**	0.40
Peak viscosity	-0.43	0.33	0.57**	-0.04
Viscosity at 95°C	-0.39	0.30	0.52*	-0.11
Breakdown viscosity	-0.51*	0.43	0.62**	-0.21
Paste viscosity at 50°C	-0.59**	0.50*	0.72**	-0.29
Set back viscosity at 40°C	-0.68**	0.60**	0.78**	-0.26

Number of cultivars = 20
* Significant at 0.05 level
** Significant at 0.01 level

Table 28: Stepwise multiple regression coefficients for the physical propertie of flakes and grain characteristics

	Intercept	Regression Coefficient	R^2	Prob > F (Level of significance)
Flake volume				
Percent floaters	1967.30	0.53 (0.19)	0.98	0.015
Bulk density of grain		-2529.96 (173.34)		< 0.001
Solubility at 90°C		4.66 (1.76)		0.018
Peak viscosity		0.10 (0.05)		0.046
Bulk density of flakes				
Floaters percentage	-581.91	-0.51 (0.19)	0.94	0.015
Bulk density of grains		1450.56 (166.80)		< 0.001
Solubility at 90°C		-4.59 (1.68)		0.016
Peak viscosity		-0.10 (0.04)		0.051
Water absorption capacity of flakes				
Stenvert hardness	148.04	-3.97 (1.70)	0.76	0.034
Endosperm texture		0.57 (0.21)		0.015
Solubility at 70°C		5.22 (1.80)		0.011
Hot paste viscosity at 95°C		-0.09 (0.04)		0.043

The values in parenthesis indicate standard error (±)

Table 29: Organoleptic qualities of sorghum flakes

Cultivar	Color and appearance	Texture		Flavor	Accepta-bility	Mean scores
		Raw	In milk			
M 35-1	4.3	3.1	3.7	4.0	3.2	3.7
SPV 475	3.3	3.3	3.6	3.9	3.3	3.5
SPV 504	3.3	3.0	3.4	4.0	3.0	3.4
SPV 783	3.8	3.4	4.0	4.2	3.7	3.8
SPV 913	3.4	3.3	4.0	4.0	3.4	3.6
SPV 980	3.3	3.3	3.7	3.8	3.2	3.5
SPH 504	3.8	3.6	3.6	3.7	3.7	3.6
CSH 12R	4.0	3.3	3.6	3.9	3.6	3.7
CSV 8R	4.2	3.4	4.0	4.1	4.1	4.0
CSV 8R Mutant	2.2	4.7	4.8	4.0	3.9	3.9
P 721	3.7	3.4	3.8	3.8	2.8	3.5
P 721 Mutant	2.8	4.3	4.6	4.1	3.4	3.8
Nizamabad	4.1	3.7	4.2	4.1	3.8	4.0
Yellow Sorghum	4.7	3.3	3.3	4.0	3.6	3.8
CSH 1	4.1	3.7	4.0	4.0	3.4	3.8
CSH 5	4.0	3.8	4.0	4.0	3.4	3.8
CSH 6	3.8	3.2	3.6	4.0	3.7	3.6
CSV 10	3.0	3.7	4.0	4.1	3.4	3.6
CSV 11	3.3	3.6	4.0	3.9	3.3	3.6
SPH 468	4.1	3.4	3.7	4.0	3.2	3.7
Minimum	2.2	3.0	3.3	3.7	2.8	3.4
Maximum	4.7	4.7	4.8	4.2	4.1	4.0
Mean	**3.7**	**3.5**	**3.9**	**4.0**	**3.5**	**3.7**
SE ±	0.13	0.09	0.08	0.03	0.07	0.04

Values are mean scores of nine panelists
Organoleptic properties are rated on hedonic scale of 1-5
(5 is excellent; 1 is unacceptable)

Table 29a: Analysis of variance of cultivars for flaking quality

Source of variation	Mean square	d.f	F	P
Color and appearance	3.041	19	14.126	< 0.001
Texture (raw)	1.340	19	2.763	< 0.001
Texture in milk	1.200	19	2.472	0.001
Flavor	0.159	19	0.931	0.546
Overall acceptability	0.822	19	1.661	0.049
Mean scores	0.268	19	1.707	0.040

was observed for yellow sorghum. Analysis of variance showed significant variations among the cultivars for color and appearance and texture of flakes.

Flavor ratings did not vary much within the cultivars. Flavor scores had a narrow range of 3.7 to 4.2 with a mean of 4.0. The acceptability scores ranged between 2.8 (P 721) and 4.1 (CSV 8R) with a mean of 3.5. Nizamabad and CSV 8R flakes were rated the best by considering all the sensory qualities and SPV 504 flakes were rated as poor.

4.5.4 Relationship between grain characteristics, physical properties and sensory properties of flakes

Correlation coefficients between the grain characteristics, physical and sensory qualities of flakes are given in Tables 30 and 31. Bulk density, 100-grain mass, kernel thickness, starch and amylose content of grain showed positive relationship with the color and appearance and negative association with the texture of flakes.

A significant negative relationship was observed between breaking strength of grains and the texture of flakes. Per cent floaters, endosperm texture, water absorption capacity, protein, fat and total soluble sugars content of grain had negative correlation with the color and appearance and positive correlation with the texture of flakes.

Bulk density of flakes was positively correlated with the color and appearance and negatively correlated with the

Table 30: Correlation coefficients (r) between physicochemical properties of grain and sensory properties of flakes

Grain characteristics	Sensory properties of flakes				
	Color and appearance	Texture of flakes (raw)	Texture in milk	Flavor	Accept-ability
100-grain mass	0.52*	-0.54*	-0.31	0.04	0.09
Bulk density	0.80**	-0.81**	-0.69**	-0.28	-0.13
Kernel thickness	0.66**	-0.53*	-0.30	0.12	0.15
Stenvert hardness	0.16	-0.33	-0.35	-0.07	-0.22
Kiya hardness	0.28	-0.63**	-0.55*	-0.19	-0.34
Per cent floaters	-0.52*	0.76**	0.68**	0.32	0.29
Endosperm texture	-0.45*	0.60**	0.51*	0.15	0.19
Water absorption capacity	-0.75**	0.83**	0.76**	0.18	0.22
Protein	-0.58**	0.57**	0.48*	0.33	0.08
Fat	-0.75**	0.85**	0.78**	0.25	0.27
Starch	0.55*	-0.76**	-0.60**	-0.21	-0.29
Amylose	0.83**	-0.71**	-0.62**	-0.09	-0.01
Total soluble sugars	-0.77**	0.83**	0.72**	0.20	0.17

Number of cultivars 20
* Significant 0.05 level
** Significant 0.01 level

Table 31: Correlation coefficients (r) between physical properties and sensory properties of flakes

Physical properties of flakes	Sensory properties of flakes				
	Color and appearnace	Texture (raw)	Texture in milk	Flavor	Accepta-bility
Volume of 100 g flakes	-0.66**	0.82**	0.78**	0.29	0.30
Bulk density	0.57**	-0.80**	-0.78**	-0.35	-0.37
Flaking recovery	0.74**	-0.78**	-0.72**	-0.20	-0.13
Water absorption capacity	-0.29	0.55*	0.55*	0.25	0.24

Number of cultivars 20
* Significant 0.05 level
** Significant 0.01 level

texture of flakes. Water absorption capacity of flakes also showed positive correlation with the texture of flakes.

Stepwise multiple regression analysis between sensory qualities of flakes and grain characteristics revealed the following facts (Table 32).

- Breaking strength and water absorption capacity of grain along with solubility of starch at 90°C and hot paste viscosity of flour at 95°C together showed significant relationship (R^2 = 0.91) with the color and appearance of flakes.

- Floaters percentage, water absorption capacity and starch content of grain along with the pasting temperature showed strong association (R^2 = 0.93) with the raw texture of flakes.

- Crispness retention of flakes in milk showed association with the water absorption capacity of grain, swelling power and solubility of starch at 80°C and peak viscosity of flour (R^2 = 0.80).

- Flavor of flakes did not show any significant relationship with grain characteristics (R^2 = 0.57)

- Floaters percentage, bulk density, starch content of grain along with the pasting temperature of flour together showed weak relationship (R^2 = 0.70) with the acceptability of flakes.

Table 32: Stepwise multiple regression coefficients for the sensory qualities of sorghum flakes and grain characteristics.

	Intercept	Regression coefficient	R^2	Prob > F (Level of significance)
Color and appearance:				
Breaking strength	4.03	-0.18 (0.05)	0.91	0.002
Water absorption capacity of grain		-0.04 (0.01)		0.001
Solubility at 90°C		0.07 (0.03)		0.012
Hot paste viscosity at 95°C		0.004 (0.004)		< 0.001
Texture raw:				
Floaters percentage	12.41	0.004 (0.002)	0.93	0.040
Water absorption capacity of grain		0.04 (0.01)		< 0.001
Starch		-0.05 (0.01)		< 0.001
Pasting temperature		-0.10 (0.03)		0.001
Texture in milk:				
Water absorption capacity of grain	3.64	0.03 (0.01)	0.80	0.001
Swelling power at 80°C		-0.24 (0.07)		0.003
Solubility at 80°C		0.17 (0.04)		0.001
Peak viscosity		-0.001 (0.002)		0.113
Flavor:				
Swelling power at 70°C	4.13	-0.10 (0.03)	0.57	0.010
Solubility at 70°C		0.06 (0.03)		0.102
Solubility at 80°C		0.04 (0.01)		0.005
Peak viscosity		-0.001(0.001)		0.029
Acceptability:				
Floaters percentage	24.47	0.01 (0.002)	0.70	0.005
Bulk density of grain		-8.50 (0.02)		0.013
Starch		-0.04 (0.01)		0.005
Pasting temparature		-0.18 (0.04)		< 0.001

The values in parenthesis indicate standard error (±)

4.6 *IN VITRO* STARCH AND PROTEIN DIGESTIBILITY OF SORGHUM CULTIVARS

4.6.1 *In vitro* starch digestibility

The results of *in vitro* starch digestibility (IVSD) of sorghum grain, pops and flakes are presented in Table 33 and Figure 10. Mean IVSD of raw sorghum meal was 56 mg (maltose g^{-1}). Cultivar differences were observed in the IVSD of raw sorghum. SPV 475 meal showed higher (80 mg maltose g^{-1} meal) starch digestibility. Whereas, CSV 8R mutant meal showed the lower (18 mg maltose g^{-1} meal) starch digestibility.

A five-fold increase in reducing sugar (maltose) content corresponding to starch hydrolysis was observed after flaking and popping of sorghum. The IVSD of sorghum flakes ranged from 183 to 326 mg (maltose g^{-1}) with a mean of 290 mg (maltose g^{-1}). Whereas popping of sorghum resulted in the IVSD varied between 130 and 386 mg (maltose g^{-1}) with a mean of 317 mg (maltose g^{-1}). Higher IVSD of 386 mg (maltose g^{-1}) among the processed samples was observed in CSV 11 pops.

4.6.1.1 Relationship between *in vitro* starch digestibility and grain characteristics

Correlation coefficients determined revealed the following facts about the *in vitro* starch digestibility of grain, flakes and pops (Tables 34 and 35).

Table 33: *In vitro* starch digestibility of sorghum grain, pops and flakes

Cultivar	Maltose released (mg g^{-1})		
	Grain	Pops	Flakes
M 35-1	71	346	325
SPV 475	80	322	290
SPV 504	49	324	308
SPV 783	63	298	317
SPV 913	52	295	290
SPV 980	72	333	249
SPH 504	51	329	284
CSH 12R	66	285	308
CSV 8R	66	331	326
CSV 8R Mutant	18	169	183
P 721	47	315	293
P 721 Mutant	20	130	183
Nizamabad	56	335	312
Yellow Sorghum	70	351	318
CSH 1	65	349	306
CSH 5	56	362	314
CSH 6	61	377	309
CSV 10	38	347	294
CSV 11	59	386	282
SPH 468	68	353	306
Minimum	18	130	183
Maximum	80	386	326
Mean	**56**	**317**	**290**
SE ±	3.6	14.1	9.1

Values are mean of three determinations

Fig.10. In vitro starch digestibility of sorghum grain, flakes and pops

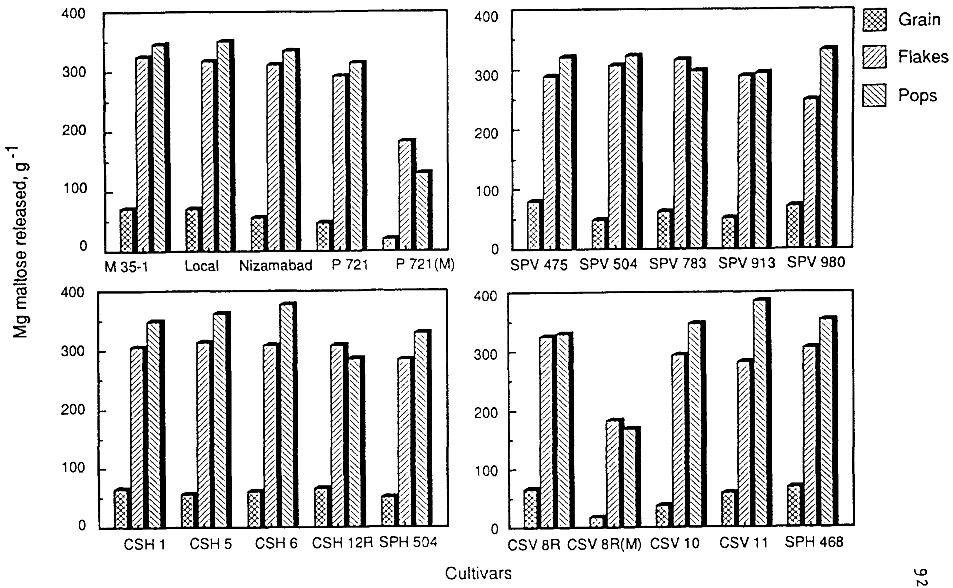


Table 34: Correlation coefficients (r) between pasting characteristics of flour and In vitro starch digestibility of grains, flakes and pops

Pasting properties of flour	In vitro starch digestibility		
	Grain	Flakes	Pops
Pasting temparature	-0.72**	-0.87**	-0.82**
Peak viscosity	0.52*	0.65**	0.55*
Viscosity at 95°C	0.54*	0.56**	0.46*
Breakdown viscosity	0.67**	0.62**	0.58**
Paste viscosity at 50°C	0.65**	0.69**	0.70**
Set back viscosity at 40°C	0.75**	0.80**	0.72**

Number of cultivars = 20
* Significant at 0.05 level
** Significant at 0.01 level

Table 35: Correlation coefficients (r) between in vitro starch digestibility (IVSD) and physicochemical characteristics

Characteristics			(r)
IVSD of grain	vs	Amylose	0.76**
	vs	Starch	0.47*
IVSD of pops	vs	Poped volume	0.71**
	vs	Popping per cent	0.84**
	vs	Expansion ratio	0.69**
	vs	Bulk density of pops	-0.89**
	vs	Amylose	0.89**
IVSD of flakes	vs	Bulk density of flakes	0.73**
	vs	Water absorption capacity of flakes	-0.36
	vs	Amylose	0.90**
	vs	Starch	0.68**

Number of cultivars = 20
* Significant at 0.05 level
** Significant at 0.01 level

- Pasting temperature of flour had a highly significant negative correlation with the *in vitro* starch digestibility of grain (r = -0.72**), flakes (r = -0.87**) and pops (r = -0.82**).

- Paste viscosity of flour at different reference points (peak viscosity, hot paste viscosity at 95°C, breakdown viscosity and cold paste viscosity) showed significant positive association with the *in vitro* starch digestibility of grain, flakes and pops.

- Starch and amylose content of grain had significant correlation with the *in vitro* starch digestibility of grain, pops and flakes.

- *In vitro* starch digestibility of pops was positively correlated with the popped volume, expansion ratio and popping per cent.

- A significant positive correlation was observed between the bulk density of flakes and *in vitro* starch digestibility of flakes.

4.6.2 *In vitro* protein digestibility

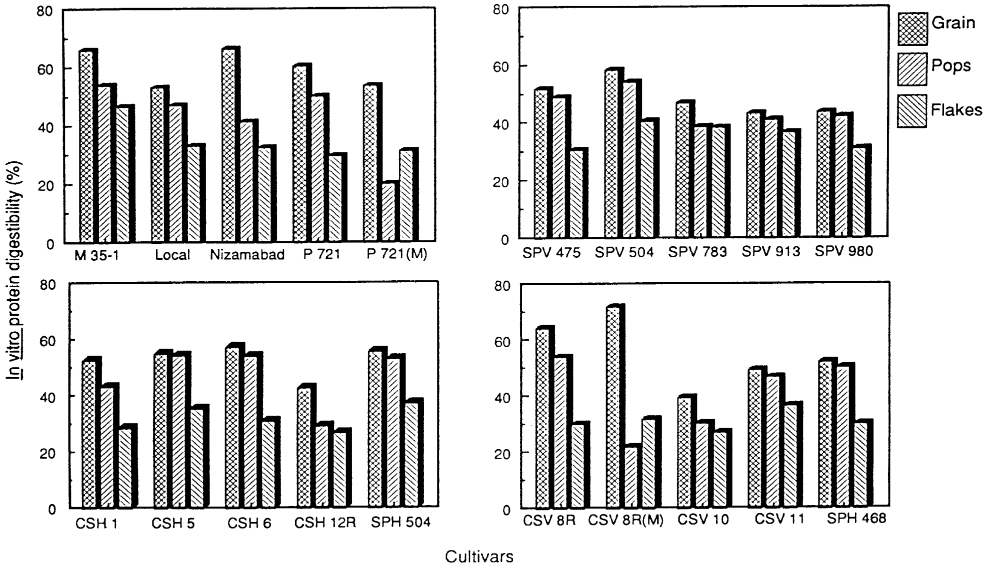
Table 36 gives the *in vitro* protein digestibility (IVPD) of sorghum grain, pops and flakes (Figure 11). Two hours pepsin digestibility of raw sorghums ranged from 39.7 per cent for CSV 10 to 72 per cent for CSV 8R mutant with a mean of 54.3 per cent.

Table 36: *In vitro* protein digestibility of sorghum grain, pops and flakes

Cultivar	*In vitro* protein digestibility (%)				
	Grain	Pops	Reduction	Flakes	Reduction
M 35-1	66.0	54.0	18.2	46.7	29.2
SPV 475	51.9	49.1	5.4	30.8	40.7
SPV 504	58.5	54.3	7.2	40.7	30.4
SPV 783	47.0	38.8	17.4	38.5	18.1
SPV 913	43.4	41.2	5.1	36.8	15.2
SPV 980	43.9	42.4	3.4	31.2	28.9
SPH 504	55.6	52.9	4.9	37.2	33.1
CSH 12R	42.7	29.3	31.4	26.8	37.2
CSV 8R	64.5	54.1	16.1	30.3	53.0
CSV 8R Mutant	72.0	22.2	69.2	32.1	55.4
P 721	60.6	50.2	17.2	29.8	50.8
P 721 Mutant	53.8	20.1	62.6	31.4	41.6
Nizamabad	66.4	41.5	37.5	32.6	50.9
Yellow Sorghum	53.2	47.1	11.5	33.2	37.6
CSH 1	52.6	43.2	17.9	28.6	45.6
CSH 5	54.9	54.2	1.3	35.4	35.5
CSH 6	57.2	54.0	5.6	31.1	45.6
CSV 10	39.7	30.6	22.9	27.3	31.2
CSV 11	49.5	47.0	5.1	36.9	25.5
SPH 468	52.3	50.5	3.4	30.3	42.1
Minimum	39.7	20.1	1.3	26.8	15.2
Maximum	72.0	54.3	69.2	46.7	55.4
Mean	54.3	43.8	18.2	33.4	37.4
SE ±	1.94	2.41	4.26	1.10	2.50

Values are mean of three determinations
Casein digestibility is 85%

Fig. 11. *In vitro* protein digestibility of sorghum grain, flakes and pops



The mean IVPD of sorghum pops was 43.8 per cent with higher value for SPV 504 pops (54.3 per cent) and lower value for P 721 mutant pops (20.1 per cent). The IVPD of sorghum flakes ranged between 26.8 per cent (CSH 12R) and 46.7 per cent (M 35-1) with a mean value of 33.4 per cent. Popping and flaking of sorghum reduced the protein digestibility by 18.2 per cent and 37.4 per cent respectively. A higher reduction (69.2 per cent) in IVPD on processing was observed in P 721 mutant pops and lower reduction (1.3 per cent) in IVPD was observed in CSH 5 pops.

DISCUSSION

CHAPTER V

DISCUSSION

Grain sorghum is an important staple food for more than seven hundred million people of the semi-arid tropics. Since a large number of varieties and hybrids with improved agronomic traits are being evolved by breeders, a part of excess production can be used alternatively for several uses including popping and flaking. Processing of grain results in a chain of interactions between several constituents of the food which affect the bio-availability of certain nutrients. It is therefore essential to study the influence of grain characteristics on processing and nutritive quality of sorghum cultivars.

5.1 PHYSICAL PROPERTIES

Simple, rapid and reliable tests to relate sorghum grain characteristics with the product quality in various end uses are greatly needed. In addition to the intrinsic chemical components, the physical properties of grain that contribute to the food quality are color, endosperm texture, presence or absence of testa, hardness and water absorption. These physical characteristics influence both primary and secondary processing of grains for food.

A wide range of cultivar variations were observed in the physical properties of grain. The correlation coefficients between 100-grain mass and other physical properties were relatively low and statistically insignificant. These results were in confirmation with the findings of Stroshine *et al.* (1981), Pomeranz *et al.* (1986) and Dorsey-Redding *et al.* (1991) with corn. However, Paulsen *et al.* (1982), and Paulsen and Hill (1985) observed positive correlations for kernel weight with floaters percentage and test weight respectively.

Bulk density (test weight) showed positive association with grain hardness and negative association with per cent floaters and endosperm texture (per cent flouriness). The previous studies of Stroshine *et al.* (1981), Paulsen *et al.* (1982) and Pomeranz *et al.* (1986) also reflect similar relationships with corn.

Murty *et al.* (1984) found relatively low and statistically insignificant correlations between breaking strength and corneousness, pearling losses and flour particle size. However, in the present study the correlation coefficients between breaking strength and other physical properties were statistically significant.

Stenvert hardness values showed positive relationship with breaking strength, bulk density and negative relationship with per cent floaters and per cent flouriness (endosperm texture). These observations confirms the earlier findings of Kirleis and Crosby (1982), Hallgren and Murty (1983) with sorghum and Pomeranz *et al.* (1986) and Dorsey-Redding *et al.* (1991) using corn.

Dehulling recovery of grains had shown positive association with grain hardness and negative association with floaters percentage and endosperm texture. Murty *et al.* (1984) also reported negative association between pearling loss and per cent corneous endosperm.

5.2 CHEMICAL COMPOSITION

Cultivar differences were observed in nutrient composition of sorghum for all the parameters studied. Protein content of the sorghum grain varied considerably among the cultivars. Protein showed a significant negative correlation with starch and amylose contents in the grain. This confirms the earlier observations of Subramanian and Jambunathan (1982 and 1984).

Starch and amylose content of the cultivars ranged from 57.5 to 76.2 and 19.4 to 30.9 per cent respectively. Miller and Burns (1970) observed that amylose content was directly related to starch content in sorghum. Such a direct relationship was also observed in the present study. Starch and amylose showed an inverse relationship with fat content. The content of soluble sugars had positive relationship with protein and negative relationship with amylose content in the grain. Similar observations were made by Subramanian and Jambunathan (1982).

5.2.1 Relationships among the physicochemical characteristics

The 100-grain mass showed positive association with starch and amylose and negative association with protein content in the grain. Subramanian and Jambunathan (1982) also reported similar relationships for 100-grain weight with protein and amylose. Endosperm texture (per cent floury endosperm) showed positive correlation with total soluble sugars, fat and negative correlation with amylose content. Similar trend was reflected in the data obtained by Cagampang and Kirleis (1984). They found that the per cent vitreousness was inversely related to total soluble sugars, fat and directly related to amylose.

In the present study bulk density of grain had positive correlation with starch, amylose and negative correlation with protein and fat contents. However, the test weight in maize was negatively correlated with protein in the study of Weller *et al.* (1988) and positively correlated in the study of Dorsey-Redding *et al.* (1991).

Water absorption capacity of grain had shown positive association with total soluble sugars, fat and negative association with starch and amylose contents. However, Dorsey-Redding *et al.* (1991) reported that water absorption capacity of corn was not related to any other quality factors.

5.3 STARCH PROPERTIES

The quality of sorghum foods may be related to differences in physical properties of starches such as gelatinization, specific heat, swelling power, solubility and pasting behaviour. These properties are important because they indicate utility of products in specific applications and reflect properties encountered by the user during the preparation of usable products. Swelling power, solubility and pasting characteristics were determined in the present study to relate these properties to the popping and flaking quality of sorghum.

The swelling power and solubility of starches considerably increased with the increase in temperature. The swelling power was significantly correlated with solubility at different temperatures indicating the starch granules that swell more have more solubility. The bonding forces within the starch granules influence the manner of swelling as mentioned by Leach *et al.* (1959). Swelling power at higher temperatures represent progressive relaxation of the bonding forces within the granules (Lorenz, 1981).

The swelling power and solubility of starches showed wide variation among the cultivars. The difference in swelling behaviour among the cultivars appear to be caused by differences in lipid and amylose contents as well as in granular organization (Dengate, 1984). The swelling power of different sorghum starches at 80^{o}C were lower than that obtained by Akingbala *et al.* (1982). Whereas, solubility values represent a similar pattern. However, P 721 mutant and CSV 8R mutant starches showed very low swelling and solubility as compared to other cultivars at 70, 80 and 90°C. Abd-Allah *et al.* (1986) observed that starches having low swelling and solubility at temperatures below 70°C had high swelling and solubility characteristics at temperatures from 80-90°C. This could be related to the two stage relaxation of bonding forces that occurred in the starch granules during swelling (Belelia *et al.*, 1980). However, this pattern was not observed with mutant cultivars in the present study.

Amylose content of the grain showed positive relationship with the swelling power and solubility of starches. In contrast to this, Akingbala *et al.* (1982) reported a highly negative correlation for amylose content of starch with swelling power and solubility. In the present study, though the amylose content of the grain was low in P 721 mutant and CSV 8R mutant, the high lipid content in these could be the reason for the low swelling and solubility pattern observed. However, Biliaderis *et al.* (1986) pointed out that amylose in starch form complex with lipid, thus the crystallite formed reduces the swelling and solubilization of starch in water .

5.3.1 Pasting characteristics of sorghum flour and starch

Pasting behaviour of starch and flour samples had shown great variation among the cultivars. Meredith and Pomeranz (1982) suggested that the part of the variation in pasting can be explained by differences in protein content and starch damage. Wada *et al.* (1979) reported that the gelatinization temperature of unisolated starch (flour) was higher than that of the isolated starch. This trend was not prominent in the present study with the pasting temperature of samples using viscoamylograph. CSV 8R mutant and P 721 mutant flours, CSV 8R mutant starch showed an exceptionally high initial temperature of pasting (swelling) compared to other cultivars. This might have been due to high fat content of mutant grain. Similarly, Eliasson *et al.* (1981) also showed that granules with higher levels of extractable surface lipids exhibited delayed gelatinization and viscosity increase. According to Desikachar (1975), Ali and Wills (1980), high gelatinization temperature in sorghum has been considered as an undesirable property because it prolongs the cooking time of sorghum during processing.

The soft grain samples exhibited high paste viscosity at different temperatures with the exception of the two mutant cultivars (P 721 and CSV 8R mutant). Goering *et al.* (1975) suggested that the peak in viscosity may occur as a result of thermal breakdown of amylose-lipid complex in wheat and barley. However, the two mutant flours showed very low peak viscosity, and paste viscosity at different temperatures compared to other cultivars. These mutant cultivars exhibited a second peak in the cooling cycle. Such a peak had been reported by Takahashi and Seib (1988) when the wheat starch was impregnated with 2 per cent lipids. On cooling, as the temperature is reduced at some point, the amylose-lipid complex loses solubility and crystallizes. The granules swell less and some water of hydration of molecules may be released into the continuous phase, which causes a reduction in paste viscosity in the cooling cycle as indicated by Takahashi and Seib (1988). Similar phenomenon could be related to the low viscous nature and the occurrence of second peak in the mutant flours. This phenomenon was not reflected when the isolated starches from these mutants are heated. This shows that the high lipid content in the whole meal flour is playing an important role.

Lipid removal from the flour samples (by soxhlet extraction) gave a some what increased paste viscosity and reduced pasting temperature. Medcalf *et al.* (1968) and Melvin (1979) also reported that lipid removal from corn and wheat starches reduced the pasting temperature but increased the pasting peak, paste consistency and set back viscosity.

When the two mutant cultivars are excluded from the data, the endosperm texture (Per cent floury endosperm) showed significant positive correlation with peak Viscosity (r = 0.62**) and hot paste viscosity at 95^{o}C (r = 0.55*).

Stenvert hardness had shown significant negative correlation with the peak viscosity (r = -0.54*) and cold paste viscosity at 40°C (r = -0.53*). Cagampang and Kirleis (1984) also observed a highly significant correlation between brabender viscosities and per cent vitreousness. However, in the present study, the correlation coefficients for paste viscosity with endosperm texture, stenvert hardness and kiya hardness were relatively low and statistically insignificant when the mutant cultivars are included.

5.4 POPPING QUALITY

The quality of popped cereals include factors such as popped volume, shape of the popped kernels, tenderness and flavor. Among these factors only the volume can be reliably measured. Reeve and Walker (1969) indicated that the optimum conditions for maximum popping varied for each kind of cereal because of variations in moisture contents and other compositional factors. In the present study, popping of sorghum was performed at 16 per cent moisture level and 240°C temperature for 2 minutes. According to Hoseney *et al.* (1983), moisture is required to generate superheated steam as a driving force for expansion. Apart from moisture, popping temperature and integrity of grains are also the critical factors controlling the popping quality.

A wide range of cultivar differences were observed in the popped volume and percentage of popping in sorghum. Among the cultivars, CSH 6, CSV 8R, Yellow sorghum, CSV 11, SPH 504 and SPH 468 were found to be good for popping. Grains of these cultivars yielded higher popped volume and popping per cent compared to other cultivars. Whereas, P 721 mutant and CSV 8R mutant grains did not expand into full flowery pops. Instron values for measuring crispness of pops also showed variations among the cultivars. Popping of sorghum resulted in reduction in moisture content of grain there by exaggerating the contents of other nutrients (protein, starch, fat and crude fiber).

5.4.1 Relationship between grain characteristics and physical properties of sorghum pops

Previous studies have shown that the physical properties of grain affect the expansion volume and unpopped kernel ratio during popping (Eldredge and Thomas, 1959; Haugh *et al.*, 1976; Murty *et al.*, 1982; Thorat *et al.*, 1988). Murty *et al.* (1982) reported that good popping sorghums will be small in size, have medium thick pericarp and hard endosperm. No significant relationship was observed in the present study between kernel dimensions and expansion volume of popped grains. Whereas, kernel thickness had positive correlation with the popping per cent. Pordesimo *et al.* (1990) observed higher expansion volumes for smaller, shorter and broader grains with microwave popping. Greater structural stability of spherically shaped structures to resist internal pressures would be the reason for this relationship.

A positive correlation between 100-grain mass and popping per cent was obtained in the present study. Verma and Singh (1979) also reported that 1000-grain weight had positive bearing on popping expansion of corn. In contrast to this, Thorat *et al.* (1988) had shown strong negative relationship for grain weight with popping per cent and expansion ratio of pops.

Bulk density of grain showed strong association with the expansion volume, popping per cent and expansion ratio of popped grain . This confirms the earlier observations of Eldredge and Thomas (1959), Haugh *et al.* (1976) using corn and Thorat *et al.* (1988) using sorghum. Denser starch granules in the grains could be the reason for this.

Reeve and Walker (1969) pointed out that the differences in distribution of horny and floury endosperm, and differences in their protein contents influence the capacity to expand when different cereals are popped. Grains with small proportion of floury endosperm had higher expansion volume, percentage of popping and expansion ratio. The large proportion of floury endosperm in the mutant grains had adverse effects on the popped volume and popping per cent. Murty *et al.* (1982) using sorghum and Pordesimo *et al.* (1991) with corn also reported similar observations. Using electron microscopy, Hoseney *et al.* (1983) found that the starch granules in the translucent endosperm were expanded into thin films while that in the opaque endosperm were not expanded at all and remained birefringent. Floaters percentage showed inverse relationship with the expansion volume, popping per cent and expansion ratio of pops. This confirms the earlier observations of Thorat *et al.* (1988) indicating that the grains with large proportion of floury endosperm do not pop and expand well.

In the present study, amylose content of grain plays an important role in the popping quality of sorghum. Popping per cent, expansion volume and expansion ratio of sorghum pops had shown strong positive correlation with amylose content of grain. However, the relationship of starch qualities to expansion properties are not completely understood. Mercier and Fillet (1975), Chinnaswamy and Hanna (1988) pointed out that starch content and quality factors (amylose and amylopectin) most significantly affect the expansion properties of extruded products. In contrast to this, Matz (1959) with corn, Mottern *et al.* (1967) with paddy, Viraktamath *et al.* (1972) with sorghum and Malleshi and Desikachar (1981) with ragi (finger millet) reported that amylose content was not related to popping quality. However, Malleshi and Desikachar (1985) observed negative relationship between popping expansion and amylose content.

Earlier workers (Srinivas *et al.*, 1974; Viraktamath *et al.*, 1972; Malleshi and Desikachar, 1981; Matz, 1959; and Malleshi and Desikachar, 1985) have shown that protein content was not related to popping expansion. However, in the present study, protein and fat content of grain had negative relationship with the popping per cent and expansion volume of pops. This probably because of the inverse relationship between starch and protein content of the grain. These observations were in agreement with the findings of the previous researchers, that the expansion volumes of cereals and starches decrease with increasing amounts of proteins (Faubion *et al.*, 1982; Peri *et al.*, 1983) and lipids (Mercier *et al.*, 1980; Linko *et al.*, 1981) but increase with increasing starch content (Linko *et al.*, 1981).

Swelling power and solubility of starch at different temperatures (70, 80 and 90^{o}C) and paste viscosity of flour showed significant positive association with the popped volume, popping per cent and expansion ratio of pops. Microscopic studies of Reeve and Walker (1969) showed that, on popping, considerable swelling of starch granules occurred and the gelatinized starch granules expand directly to form characteristic soap bubble structures. Whereas, the grains of two mutant cultivars that have low swelling, solubility and paste viscosity did not expand much on popping. This might have been due to the tendency of starch granules to fuse in the popped grain without forming soap bubble reticulum. This indicates that the swelling and solubility of starches has important bearing on the popping quality of sorghum.

The cohesive forces in the granular structure of starches that are responsible for high paste viscosity in the flour during heating could also be responsible for the higher expansion volumes in the popped grains. Pasting temperature of sorghum flours had negative relationship with the popped volume, popping per cent and expansion ratio of pops. The exceptionally high pasting temperature along with low paste viscosity could be related to the poor popping quality of the mutant grains. Although, the ranges of pasting temperatures were similar in other cultivars, little is known about the differences in their composition which could influence gel properties related to popping.

Stepwise multiple regression analysis shows that 95 per cent of the variation in the percentage of popping could be explained by the pasting temperature, paste viscosity of flour at 40, 50^{o}C and solubility of starch at 80^{o}C. Kernel thickness along with pasting temperature of flour, swelling power of starch at 90^{o}C, solubility of starch at 70^{o}C together contributed to 82 per cent of variation in the popped volume, and 94 per cent of the variation in bulk density of pops. Whereas, 84 per cent of the variation in the expansion ratio of pops could be accounted by the variation in paste viscosity of flour at 40, 50^{o}C and swelling power of starch at 70^{o}C along with 100-grain mass.

5.4.2 Organoleptic qualities of sorghum pops

Sensory qualities of pops showed significant variations (ANOVA) among the cultivars. CSH 6 and CSV 8R pops were bright white, large in size and were more appealing to the panelists. Whereas, CSV 8R mutant and P 721 mutant grains do not expand greatly on popping and produced dark, roasted product without expanding into flowery pops. SPH 504 pops were crisp followed by CSV 8R and CSH 6 pops. Whereas, CSV 10 pops were hard in texture. Panelists showed more preference for the flavor of CSV 8R and CSH 6 pops. The overall evaluation of pops considering all the sensory qualities rated highest preference for CSH 6 and CSV 8R pops and least preference for CSV 10 and mutant pops.

5.4.3 Relationship between sensory qualities of pops and grain characteristics

The bulk density, amylose content of grain and starch properties, were related to the sensory qualities of pops. These relationships may be explained in part by the effect of amylose content on volume expansion during popping or bulk density of popped sorghum. It was observed that higher the amylose content of sorghum, higher is the paste viscosity, the greater is its volume expansion during popping. Both the mutant cultivars with low amylose content, high protein and fat showed the least expansion on popping.

A significant positive relationship was observed between crispness of pops using Instron and sensory texture of pops, popped volume and expansion ratio of pops. However, the grain characteristics were not related to crispness of pops using Instron.

Stepwise multiple regression analysis indicates that bulk density of grain, solubility of starch at 70°C, pasting temperature and hot paste viscosity of flour at 95°C together explained 93 per cent of the variation in color and appearance of pops. Whereas, breaking strength and water absorption capacity of grain along with swelling power of starch at 70°C and solubility of starch at 80°C account for 83 per cent of variation in the texture of pops. Bulk density of grain along with swelling power of starch at 70°C, breakdown viscosity and paste viscosity of flour at 50°C contribute to 89 per cent of variation in flavor and 88 per cent of variation in acceptability of pops.

5.5 FLAKING QUALITY

In the preparation of sorghum flakes, the grains were pressure cooked and conditioned prior to flaking. However, Hale (1970) observed, that the advantage of pressure cooking of sorghum grain prior to flaking is related to the toughness of the flakes. Very little is known about the physicochemical characteristics of grain that influence the flaking quality of sorghum.

Sorghum cultivars showed wide differences in the flaking quality. Bulk density i.e. weight per volume of the flakes is an index of flake flatness and lower bulk density is the criteria for good flaking quality. Among the non mutant cultivars, Nizamabad, M 35-1, CSH 6, yellow sorghum and SPH 468 produced strong flakes with lower bulk density. The flaking recovery and water absorption capacity of these cultivars was reasonably good and are suitable for flaking. Although, the P 721 mutant and CSV 8R mutant cultivars produced the flakes with lower bulk density, these cultivars are not suitable for flaking because of lower dehulling and flaking recovery. The flakes produced are weak and breaks easily during handling and packing.

Flaking of sorghum reduced the protein, fat, crude fiber contents and increased the starch content. The dehulling process involved in the preparation of flakes resulted in reduction of dietary fiber, ash, ether extract (fat) and protein fractions there by exaggerating the starch content.

In general, the grains with small proportion of floury endosperm, higher bulk density and lower water absorption capacity produced flakes with higher bulk density (lower flake volume) and lower water absorption capacity. The low water uptake of these grains during soaking followed by incomplete gelatinization of starch during subsequent pressure cooking and flaking could be the reason for the lower flake volume and higher bulk density. Whereas, in soft grain varieties the floury nature of the endosperm, with high water absorption capacity, permits gelatinization of starch to occur and improves the flake volume. Rooney and Pflugfelder (1986) however, indicated that the critical factors affecting steam flaking relate directly to the water uptake into the endosperm, which permits gelatinization to occur.

It may be noted that boldness of grain is also one of the major factors in determining the suitability of the varieties for flaking. Varieties having too small grains and hard in texture tend to give relatively lesser flaking yield and produce flakes that are hard in nature.

Starch and amylose contents of grain showed positive relationship with the bulk density of flakes. Whereas, fat and soluble sugars content had negative relationship with the bulk density of flakes. Swelling power and solubility of starch at 70, 80 and 90°C and paste viscosity of flour at 40 and 50°C showed positive correlation with the bulk density of flakes. P 721 mutant and CSV 8R mutant cultivars are largely contributing to this relationship. Whereas, when these two mutants are excluded from the data, correlation coefficient between swelling power, solubility and bulk density of flakes were relatively low and insignificant.

Pressure flaking involves movement of heat and water into the grain , causing swelling of starch. Rolling of the hot, moist grains tears apart some of the swollen granules forming a paste that binds the other material into a strong flake. Whereas, in mutant cultivars the shriveled nature of the grains with improper starch deposition and low starch swelling and solubility properties would be responsible for the formation of insufficient starch glue during pressure flaking. This in turn forms very thin and flat flakes with very low bulk density and breaks easily during handling and packing.

The floaters per cent and bulk density of grain along with the solubility of starch at 90°C and peak viscosity of flour together contribute to 94 per cent of variation in the bulk density of flakes. Whereas, only 76 per cent of the variation in the water absorption capacity of flakes could be explained by the variation in the stenvert hardness, endosperm texture, solubility of starch at 70°C and hot paste viscosity of flour at 95°C.

5.5.1 Organoleptic qualities of sorghum flakes

Analysis of variance showed significant cultivar differences in the color and appearance and texture of sorghum flakes. In general sorghum flakes were creamy white in color. Whereas, mutant flakes were darker (yellowish brown) in color compared to other flakes. Pressure cooking, flaking and drying reduced color brightness and increased brownness and yellow hues, probably due to reactions of sugars with amino acids.

CSV 8R mutant and P 721 mutant flakes were crisp compared to other flakes. These flakes had soggy texture in milk. Whereas, the flakes of non-mutant cultivars retained their shape and crispness in milk. Panelists could not differentiate the flavor of flakes among the cultivars. Nizamabad and CSV 8R flakes were more preferred and SPV 504 flakes were least preferred by the panelists.

5.5.2 Relationship between sensory qualities of flakes and grain characteristics

Color and appearance and texture of flakes showed some relationship with starch properties, bulk density, water absorption capacity, amylose and fat contents of the grain. Flakes prepared from the grains with higher bulk density, and higher amylose content were bright in color. Mutant flakes that have high fat, protein, soluble sugars and low amylose contents were dark in color and had highly crisp texture that breaks easily. This may be related to the expansion of grain during pressure cooking and further flaking process.

Stepwise multiple regression analysis shows that 91 per cent of the variation in color and appearance of flakes could be explained by the water absorption capacity, breaking strength of grain, solubility of starch at 90°C and hot paste viscosity of flour at 95°C. Whereas, 93 per cent of the variation in raw texture of flakes could be explained by the contribution of the floaters per cent, water absorption capacity and starch content of grain along with the pasting temperature of flour. Swelling power and solubility of starch at 80°C, peak viscosity of flour and water absorption capacity of grain together account for only 80 per cent of the variation in texture of flakes in milk.

Flavor of flakes showed weak association (R^2 = 0.57) with swelling power of starch at 70°C, solubility of starch at 70, 80°C and peak viscosity of flour. General acceptability of flakes also showed some association (R^2 = 0.70) with floaters per cent, bulk density and starch content of grain and pasting temperature of flour.

5.6 *IN VITRO* STARCH DIGESTIBILITY OF SORGHUM CULTIVARS

Digestibility of starch is affected by the composition of starch, protein-starch interactions, structural integrity of the endosperm, anti-nutritional factors, and processing history of the product (Rooney and Pflugfelder, 1986 and Waniska *et al.*, 1990). Heat, moisture, mechanical action and chemical agents are often used in combination to process cereals. Gelatinization or any other treatment that destroys the granular structure of starch increases the susceptibility of starch to enzyme action. The *in vitro* methods of starch hydrolysis provides useful means of assessing the degree of gelatinization of starch in a product, in predicting bio-availability of starch *in vivo*. Significant correlation between starch availability *in vitro* and *in vivo* was observed (O'Dea *et al.*, 1981).

The *in vitro* starch digestibility (IVSD) of ground sorghum showed large variation among the cultivars. Numerous comparisons of sorghum cultivars have been made by earlier workers (Hinders, 1968; Hibberd *et al.*, 1982; Samford *et al.*, 1970) using *in vitro* digestibility . Wagner (1984) also reported large variation in the *in vitro* dry matter disappearance (IVDMD) of ground sorghum.

The mean IVSD of sorghum grain was 56 mg (maltose g^{-1} meal). Osman *et al.* (1970), Roy (1985) and Kamini Devi (1990) also reported low values for IVSD of whole grain sorghum as 10.0, 11.1 and 21.2 per cent respectively. However, the structural integrity of the endosperm appears to be the primary factor limiting sorghum starch digestibility (Waniska *et al.*, 1990). In raw grain , the surface of the starch granule is often less susceptible to degradation than the inner part of the granule (Gallant *et al.*, 1982). In the peripheral endosperm of sorghum the starch granules are embedded in a dense mixture of protein bodies (Kafirins). The matrix protein makes the starch difficult to hydrolyze by enzymes (Rooney and Miller, 1982).

In the present study, endosperm texture (per cent floury endosperm) showed negative relationship with the *in vitro* starch digestibility of grain. This observation is however, contradictory to the findings of Waniska *et al.* (1990). They reported higher starch hydrolysis rates for sorghums with softer endosperm texture than vitreous endosperm texture. Whereas, Rooney and Pflugfelder (1986) concluded that no consistent pattern has been established for the *in vitro* digestibility of non waxy sorghums with intermediate endosperm texture. The effect of environmental conditions during maturation of the sorghum grain is also an important determinant of digestibility. The lower digestibility of mutant grains may be due to the shriveled nature of the grain with improper starch deposition, low starch, high fat and protein contents in the grain.

Digestibility of starch is generally inversely proportional to amylose content (Rooney and Pflugfelder, 1986). However, in the present study a significant positive relationship was observed between amylose content and *in vitro* starch digestibility of grain. IVSD of grain, pops and flakes was directly related with the paste viscosity of flour at different temperatures and inversely related to pasting temperature. This indicates that the amylose content, viscosity of flour at different temperatures and pasting temperature are the important characteristics to assess the digestibility and quality of starch.

A five-fold increase in reducing sugar (maltose) content corresponding to starch hydrolysis was observed after popping and flaking of sorghum. Similar findings were reported by McNeill *et al.* (1975), Delort-Laval and Mercier (1976), Holm *et al.* (1985), Roy (1985) and Kamini Devi (1990). Although, the P 721 mutant and CSV 8R mutant grain showed lower IVSD, on popping and flaking the IVSD increased by approximately 9 folds. This indicates that some degradation of starch had occurred in these processes. Colonna *et al.* (1984) also reported macromolecular degradation of wheat starch, without formation of oligosaccharides, during extrusion cooking.

In vitro availability of starch in flaked sorghum (290 mg maltose g^{-1} flakes) was slightly lower than that in popped sorghum (317 mg maltose g^{-1} pops). Similar observations were made by Holm *et al.* (1985) using wheat. Earlier studies of Delort-Laval and Mercier (1976) had shown an increase in amylolysis rate of starch due to extrusion, popping and flaking of wheat to 79, 56 and 52 per cent respectively. However, Farber and Gallant (1976) observed that, after flaking of barley and maize, the protein matrix seemed to be reticulated and fragmented. Whereas, after popping it appeared to be stretched. The differences in starch availability between popped and flaked sorghum in the present study may be related to the differences in the degree of gelatinization.

Popping expansion showed significant correlation with the *in vitro* starch digestibility of pops. According to Holm *et al.* (1988) the extensive fragmentation of the starch resulting from the instantaneous shear forces arising from the expansion of grain during popping could be the reason for the increased reducing sugar content (maltose) in the popped sample. When the grain was slightly expanded, only slight fragmentation of starch has occurred resulting in low starch digestibility.

In general the degree of gelatinization in flaked cereals increases with the decrease in flake thickness. The low IVSD of mutant flakes, though the flake thickness was very low, may be due to the low starch content in the grain and shriveled nature of the grain with improper starch deposition.

5.7 *IN VITRO* PROTEIN DIGESTIBILITY OF SORGHUM CULTIVARS

Digestibility of a food protein determines the availability of its amino acids which in the final analysis is to be established by feeding trials. However, *in vitro* methods of protein evaluation are also important and useful because of their rapidity and sensitivity. Changes in protein quality that occur during cooking have interested many scientists (Maclean *et al.*, 1981; Hamaker *et al.*, 1987). An empirical *in vitro* pepsin digestibility procedure developed by Axtell *et al.* (1981) and Mertz *et al.* (1984) was found to closely simulate Maclean's value for sorghum, wheat, maize and rice in children. Hence, the *in vitro* method of Axtell *et al.* (1981) was used to determine the protein digestibility of sorghum cultivars before and after processing.

In vitro studies on digestibility of sorghum proteins revealed considerable variation among the cultivars, with a very low digestibility for the variety CSV 10. Earlier studies (Sherrod and Albin, 1973; McCollough *et al.*, 1973) also indicated a significant effect of genotype on the apparent digestibility of sorghum proteins.

The processing techniques used to prepare sorghum foods have significant positive (Maclean *et al.*, 1981; Graham *et al.*, 1986; MacLean *et al.*, 1983) or negative effect (Axtell *et al.*, 1981; Vivas *et al.*, 1988) on protein digestibility. In the present study popping and flaking of sorghum reduced the digestibility of proteins. Reduction in IVPD of sorghum was more due to flaking (37.4 per cent) than popping (18.2 per cent). This suggests that the method of processing, temperature and time of processing may be the factors that affect the protein digestibility in processed grains.

In the preparation of sorghum flakes the dehulled sorghum grains were subjected to pressure cooking (at 20 Psi for 20 minutes) prior to flaking. Kamini Devi (1990) however, reported that heating to high temperatures under pressure as in autoclaving is deleterious to protein digestibility. The formation of resistant starch due to the strong binding of starch and protein molecules during long periods of thermal pressure treatments could be the reason for the low IVPD values observed due to flaking.

Fapujuwo *et al.* (1987) reported a higher protein digestibility in extruded sorghum than raw sorghum. At high temperatures protein digestibility appears to be better due to disintegration of protein matrix and complete gelatinization of starch. High temperature (240°C) and short time (120 seconds) of heat contact as in popping of sorghum probably reduces retrogradation and complexing of starch and protein, there by preventing the loss in digestibility when compared to flaking of sorghum. According to Hsu *et al.* (1977), during puffing of rice the high temperature and short time heat process that gelatinizes the starch opens the carbohydrate-protein structure and makes it easier for proteolytic enzymes to hydrolyze the proteins.

However, Gupta *et al.* (1986) observed an increase in *in vitro* protein digestibility after popping and boiling respectively in popcorn and sweet corn kernels. Whereas, it decreased slightly in normal and 'opaque-2' maize following these treatments.

Using *in vivo* rat assays Bressani *et al.* (1987) reported the reduction in true protein digestibility of sorghum due to popping and boiling in water. Hakansson *et al.* (1987) also found that in wheat, the stronger heat treatments like popping and autoclaving reduced the protein digestibility *in vivo*. In the present study CSV 8R mutant and P 721 mutant grain on popping showed greater reduction in IVPD compared to other cultivars. The reduced protein digestibility in the severely popped sample could be due to the formation of cross linkages in the protein structure which may lead to incomplete digestion due to reduced availability of adjacent amino acids. In addition, some maillard reaction products may interfere with the digestive process, most likely due to inhibition of proteolytic enzymatic activity and reduced digestion of both exogenous and endogenous proteins in the intestine (Hakansson *et al.*, 1987). Similarly, Bressani (1990) also reported a lower protein digestibility in the high lysine sorghums when the grains were popped compared to cooked, raw and extruded. Flaking of mutant cultivars did not show much variation in IVPD when compared with other cultivars.

SUMMARY AND CONCLUSIONS

CHAPTER VI

SUMMARY AND CONCLUSIONS

Popping and flaking quality of sorghum using 19 high yielding varieties/hybrids and one local variety were studied in relation to physicochemical characteristics, and *in vitro* starch and protein digestibility. The physical properties, chemical composition and starch properties of grain showed variation among the cultivars. Physical properties such as endosperm texture, hardness, per cent floaters, bulk density and water absorption capacity of grain were highly associated among themselves and also with chemical components. The starch and amylose contents were positively associated with 100-grain mass and bulk density, and negatively associated with per cent floaters and water absorption capacity of grain.

Popping and flaking methods were standardized using the grains of SPV 475 and yellow sorghum cultivars. Grain samples were popped at 16 per cent moisture level and 240^{o}C temperature for 2 minutes. For flaking, the dehulled grains were soaked in water for three hours, pressure cooked, conditioned and flaked in a flaking machine. Pops and flakes were evaluated for their physical properties, chemical composition, organoleptic properties and *in vitro* starch and protein digestibility.

A wide range of cultivar differences were observed in popping and flaking quality of sorghum. Good quality pops should be chalky white and flowery with high popping expansion and percentage of popping. Popped volume and popping per cent in sorghum showed significant positive relationship with bulk density of grain, amylose content, swelling capacity and solubility of starch, and paste viscosity of flour. Whereas, endosperm texture, per cent floaters and protein content of grain had shown negative association with popped volume and popping per cent. Sensory qualities of pops showed significant variations among the cultivars. Bulk density and amylose content of grain, starch properties and popped volume had positive relationship with the sensory properties.

Stepwise multiple regression analysis showed that the starch properties could explain for 95 per cent of variation in popping per cent. Starch properties along with kernel thickness together contributed to 82 per cent of variation in popped volume. Whereas, starch properties along with a few physical properties together explain the variations in sensory properties of pops. These relationships may be explained in part by the effect of amylose content and starch quality on volume expansion during popping.

The property of producing lower bulk density is an important criteria for good flaking quality. The bulk density of flakes was positively associated with hardness and bulk density of grain, starch and amylose contents, and paste viscosity of flour. Whereas, per cent floaters, endosperm texture and water absorption capacity of grain had shown negative relationship with the bulk density of flakes. However, the water absorption capacity of flakes was directly related to endosperm texture, per cent floaters, water absorption capacity of grain and inversely related to grain hardness and bulk density. Significant cultivar variations were observed in the color and appearance and texture of sorghum flakes. Among the sensory properties, color and appearance and texture of the flakes showed association with starch properties, bulk density, water absorption capacity and amylose content of grain.

Multiple regression analysis revealed that floaters per cent, bulk density of grain along with solubility of starch at 90^{o}C and paste viscosity of flour together explained for 94 per cent of variation in the bulk density of flakes. Starch properties along with a few physical properties of grain contributed towards the variation in sensory qualities of flakes.

In vitro starch and protein digestibility of grain also showed variation among the cultivars. Popping and flaking of sorghum changed the starch and protein digestibility. A five-fold increase in starch digestibility was observed in both the processes. Increase in starch digestibility was more due to popping than flaking. However, popping and flaking reduced the protein digestibility of grains by 18.2 per cent and 37.4 per cent respectively.

The cultivars, CSH 6, CSV 8R, yellow sorghum, CSV 11, SPH 504 and SPH 468 produced pops with high popped volume and popping per cent. The grains of P 721, CSV 10 and SPV 913 cultivars yielded pops with poor popped volume and percentage of popping. Whereas, the grains of P 721 mutant and CSV 8R mutant did not expand into flowery pops and produced slightly expanded and roasted product. CSH 6 and CSV 8R pops were highly preferred and CSV 10 and mutant pops were least preferred by the panelists.

With regard to flaking, Nizamabad, M 35-1, CSH 6, yellow sorghum and SPH 468 cultivars produced flakes with lower bulk density among the non mutant cultivars. Although, P 721 mutant and CSV 8R mutant grain produced flakes with lower bulk density and higher water absorption capacity, these cultivars are not economical for flaking because of their low dehulling and flaking recovery. Nizamabad and CSV 8R flakes were more preferred and SPV 504 flakes were least preferred by the panelists.

However, CSV 8R mutant and P 721 mutant cultivars showed variation from other cultivars in physicochemical characteristics, popping and flaking quality and *in vitro* starch and protein digestibility. This could be because of the shriveled nature of grains with improper starch deposition, high protein and fat contents. These cultivars are not suitable for popping and flaking.

Pops and flakes have potential use as snack food and breakfast cereal. Flakes can also be used as adjuncts in brewing to substitute a part of barley and it needs further research.

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