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Sweet Potato Starch: Physico-Chemical, Functional, Thermal and Rheological Characteristics

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ABSTRACT

Among the tropical tuber crops, sweet potato comes next to cassava in starch content. The article reviews the extraction of starch from sweet potato tubers, and the physicochemical, functional, thermal and rheological characteristics of sweet potato flour and starch. Wide variation in biochemical constituents is observed depending on the origin of the tubers and processing conditions. The lipid and phosphorus contents are low. The starch granules are round, 3-45 µm in size and have distinct XRD patterns. The amylose content, swelling, solubility and digestibility characteristics depend on a number of factors like age of crop, method of extraction and varietal differences. The viscosity and rheology properties are also quite diverse among the varieties. DSC analysis indicates pasting temperature to be between 60 and 88°C while enthalpy of gelatinization is 10-18 J/g. Heat moisture treatment alters some of the properties.

Keywords: enzymatic extraction, heat-moisture treatments, mobile starch extraction plant, physico-chemical, thermal, rheological and functional properties, starch, sweet potato flour

Abbreviations: BU, Brabender units; **cP**, centi Poise; **DP**, degree of polymerization; **DSC**, differential scanning calorimetry; **FTIR**, fourier transform infrared; **G'**, storage modulus; **G"**, loss modulus; **PV**, peak viscosity; **RVA**, rapid visco analyser; **SEM**, scanning electron microscopy; **XRD**, X-ray diffraction

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INTRODUCTION

Starch occupies an important position as a major biochemical component in the plant kingdom, especially in the tuber crops. The starch content varies from 10-30% on fresh weight basis in these crops and the starches extracted from tuber crops have diverse functional properties. The application of the starch in food and industry depends primarily on the starch content and also on the starch properties. Sweet potato has the highest starch content next to cassava among the tropical tuber crops and the extraction process is relatively easy compared to cereals. In third world countries, sweet potatoes are processed into starch, noodles, candy, flour and desserts. Sweet potato starch production has assumed the status as an important cottage industry in many parts of China. China has become the largest grower of sweet potatoes, providing about 80% of the world's supply. More than 2000 varieties of sweet potatoes are available in China which can be roughly divided into 'general type', 'high starch type' and 'food consumption type' (Liu 2004).

The major biochemical component of the dry matter in sweet potato is starch and a large proportion of the starch can be extracted from the tubers. The uses of sweet potato starch are primarily determined by its physicochemical properties like granule shape and size, amylose content, molecular structure, pasting properties, retrogradation, enzyme

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Invited Review

digestibility, etc. A number of studies on the distinctive properties of sweet potato starch have been undertaken in different laboratories in the last few decades (Takeda 1986; Noda *et al.* 1992, 1996; Collado and Corke 1997; Garcia and Walter 1998; Katayama *et al*. 2002; Moorthy 2002; Katayama *et al*. 2004). This chapter attempts to bring together the present knowledge on starch derived from this crop.

STARCH EXTRACTION

The properties of sweet potato starch are very similar to cassava starch. However, though the extraction of starch from cassava is widely practiced, starch extraction from sweet potato is not so widely prevalent. The main reasons attributed are that the settling of starch is slow so that the longer residence time can possibly lead to microbial damage of starch and thereby lower the quality.

Correct time of maturity, methodology used for extraction and processing machinery are pertinent in obtaining maximum yield of starch from tubers. If harvested late, the starch in the tuber can get converted to sugar and fibre and thus affect yield and quality of starch. Delay in processing sweet potatoes after harvesting results in the accumulation of sucrose and reducing sugars (Heinze and Appleman 1943). Similarly delays between shredding and starch extraction have been reported lead to the synthesis of toxic compounds, mainly the alkaloid ipomeamarone, and the derived starch may become inedible and hazardous (Jain *et al*. 1951).

The method used in starch isolation can affect both the physicochemical properties of the starch and the level of non-starchy components, which in turn influence the physico-chemical properties of the starch indirectly (Lii and Chang 1978). Starch is generally extracted from the fresh tubers by the conventional wet processing methods. The tubers are washed, peeled and rewashed thoroughly with water to remove all the adhering soil, dirt and impurities. They are cut into small pieces 2-3 cm thick and crushed using stainless steel raspers after adding excess water (usually 10:1) The material is ground until a uniform mash is obtained and subsequently screened sequentially through 80 and 150 mesh sieves adding excess water The suspension passing through the sieve is collected in large settling tanks and allowed to settle for 8-10 h or overnight and the supernatant water decanted out. The settled starch is scooped out and is sun dried.

Over 20% increase in recovery of starch from sweet potato tubers has been obtained by an enzymatic technique using pectinase and cellulase enzymes. These enzymes act by breaking the pectin-cellulosic matrix of cell membranes resulting in the release of the starch granules. The treatment up to 0.05% concentration of enzyme gives higher yield without affecting the starch properties (Kallabinski and Balagopalan 1991; Moorthy and Balagopalan 1999; **Tables 1, 2**). Use of lime, dilute acetic acid and lactic acid during extraction has been reported to improve yield of starch (Radley 1976a).

In order to facilitate *in situ* starch extraction in the villages, a multipurpose mobile starch extraction plant was developed at Central Tuber Crops Research Institute and tested for starch extraction from sweet potato by Sajeev *et al*. (2005). The major components of the machine (**Fig. 1**) are: 1. hopper to feed the tubers; 2. crushing disc or cylinder with nail punched protrusions rotating inside a crushing chamber to crush the tubers; 3. sieving tray to remove the fibrous and other cellulosic materials, stainless steel or plastic tanks to collect and settle the sieved starch suspension; 4. tuber storage chamber; 5. handle and wheels for easy transportation from place to place; 6. frame to support these components. A sieve plate with 7 mm holes is provided at the outlet of the crushing chamber to prevent the uncrushed tuber pieces to pass along with the crushed mash in to the sieving tray. Overall dimension of the machine is 135 cm (width) × 180 cm (length). A height of 130 cm is provided so that tubers can be fed by a person standing upright on the ground. Addition of water during the processing is controlled with a water pipe with holes fixed inside the hopper along its length and during sieving by a shower attachment connected to the water line. The unit is operated by a single phase electric motor of 1 hp and 1450 rpm. A power generator (fuel: kerosene, rated power: 1.1 kW, specific fuel consumption: 700 g kW/h, 1500 rpm) is also attached to the rasper frame to use as an alternate energy source in remote and tribal areas where there is no electric power.

Table 1 Functional properties of enzymatically separated sweet potato starch.

Enzyme concentration (%)	Starch content (%)	Reducing value	Swelling volume (%)	Solubility (%)
0.000	90.33	1.37	19.50	22.5
0.010	91.00	1.35	17.50	19.5
0.025	92.05	1.50	20.50	20.2
0.050	90.92	1.85	17.85	22.3
0.100	91.25	2.25	17.75	37.5
0.200	90.85	1.95	18.25	39.5

Source: **Moorthy SN, Balagopalan C** (1999) Physicochemical properties of enzymatically separated starch from sweet potato. *Tropical Science* **39**, 23-27

Table 2 Pasting Properties of enzymatically separated sweet potato starch.

Starch concentration (%)	Enzyme concentration (%)	Peak viscosity (BU)	Breakdown viscosity (BU)	Pasting temperature (°C)
5	0.000	260	0	87-95
	0.010	280	0	86-95
	0.025	300	40	85-95
	0.050	280	40	84-95
	0.100	280	100	82-89
	0.0200	220	40	82-90
6	0.000	440	20	88-95
	0.010	460	40	87-94
	0.025	500	40	86-95
	0.050	500	100	84-92
	0.100	460	120	82-92
	0.0200	400	60	82-88
7	0.000	780	0	8895
	0.010	760	60	88-95
	0.025	740	100	84-95
	0.050	760	160	84-95
	0.100	680	200	82-90
	0.0200	600	120	82-89

Fig. 1 Multipurpose mobile starch extraction plant for sweet potato starch extraction.

Peeled tubers are cut into 3-5 cm pieces, washed and fed to the crushing chamber through the hopper keeping the water line in the feeder open during the operation. The sharp edges of the protrusions on the high speed rotating crushing cylinder tear open the cell walls of the tubers and the starch is separated by the water stream carrying the pulp down through the sieving tray to the settling tank. Water is sprayed to the tray to wash the pulp and squeezed until water draining from it is no longer milky in appearance. The starch milk is allowed to settle overnight in the settling tank and after draining the supernatant liquid, the wet starch is scooped out and sun dried.

The maximum extractable starch in the tubers as calculated by chemical method was 21.0% and the starch extracted by manual method was about 17.7%. When the tubers were crushed using mobile plant, the amount of starch extracted was 15.9% giving rise to the recovery of starch as 75.1% on the basis of the maximum extractable starch (chemical method). The reduction in the value of recovery compared to the manual method is due to the difference in the mechanism of crushing and also the less retention time of the tubers in the crushing chamber of the machine (continuous feeding) compared to batch feeding. The recovery of starch was higher than that reported by Sheriff and Balagopalan (1999) i.e. 61.2% recovery for sweet potato. Purity of starch extracted with the machines was fairly good in all the samples (82-85%). Capacity of the machine was 135 kg/h with a rasping effect of 57.98%. These rasping effect values are higher when compared to those obtained (40.2%) by Sheriff and Balagopalan (1999).

The starch paste should be clear and free from any off-colour for better acceptability in food industries. Colour is an important criterion for starch application in sago, food and textile industries (Radley 1976b). Sweet potato starch if properly processed gives pure white colour.

BIOCHEMICAL CONSTITUENTS

Though the extracted starch appears to be in the pure form free from other components, it is invariably accompanied by various other components (**Table 3**) viz., fibre, lipids, proteins and minerals depending on a number of factors like method of extraction, age of the crop, environmental conditions etc. Some of these impart desirable qualities to the starch, while others have detrimental effect on quality. Starch content in the extracted starch is usually more than 95%, but the value depends on maturity and method of extraction. The moisture content recommended for safe storage of starch is 13% (ISI 1970; Radley 1976b), but large variation has been found (Kay 1987; Takeda *et al.* 1986; Melo *et al*. 1994; Soni *et al*. 1990) in fibre and protein (0.1-0.5%) contents. The ash content of the starch from different lines was in the range 0.25-0.55%. The fibre content was found to increase with age of the crop, especially for sweet potato (Moorthy *et al*. 2010).

The phosphorous content in sweet potato is similar to cassava starch (Rickard *et al*. 1991) but less compared to Irish potato starch (Hizukuri 1969). Phosphate is believed to be an important factor in determining the granular strength by forming cross linkages. The root starches contain much smaller quantities of native lipids in them, hence the addition of lipids or surfactants enhanced the starch quality and it was that there was no hindrance for the tuber starches to complex with surfactants or lipids added externally.

Size and shape

The size and shape of starch granules from sweet potato reported by various workers are presented in **Table 4**. Madamba *et al*. (1975) found significant differences in size among all sweet potato varieties studied. Sweet potato granules are of a similar size to those of cassava and maize but are smaller than those of potato which also have a larger range of granular size (Dreher and Berry 1983). Starch grains are of variable shape (oval, round, faceted round and polygonal) and are usually non-aggregated. Earlier studies revealed that sweet potato starch is polygonal or nearly round in shape (Shin and Ahn 1983; Bouwkamp 1985; Tian *et al*. 1991; Woolfe 1992) and has a centric distinct hilum. Polarisation crosses are comparatively less distinct. Granule size ranges from 4-43 µm, depending on the cultivar. The mean size of the granule ranges between 12.3-21.5 µm. The granule size has been found responsible for some functional properties like swelling, solubility and digestibility. Bouwkamp (1985) reported negative correlation between particle size and susceptibility to amylase and acid degradation for selected sweet potato cultivars. According to Rasper (1971), particle size including size distribution, is one of the characteristics that affects the functional properties of the starch granules. Smaller granules are reported to have both high solubility and water absorption capacity (Georing and Dehaas 1972).

Table 3 Proximate composition of isolated starch.

Parameters (g kg^{-1})	Range	Reference
Moisture	139-150	Lii and Chang 1978
Ash	0.8-1	Delpeuch *et al*. 1978, 1979
	2.6-5.1	Lii and Chang 1978
Fibre	0.7-1.8	Delpeuch *et al.* 1978, 1979
	0.5-1	Lii and Chang 1978
Crude protein	4.8-5.4	Delpeuch *et al*. 1978, 1979
	1.3-2	Lii and Chang 1978
Crude lipid	0.6-6	Delpeuch *et al*. 1978, 1979
Phosphorus	0.19	Lii and Chang 1978
Starch	980-988	Delpeuch *et al*. 1978, 1979

Table 4 Physical characteristics of sweet potato starch.

Size (µm)	Shape	X-ray pattern	Reference
14-34	Round polygonal	Ca	Shin and Ahn 1983
3-42	Round polygonal	-	Seog *et al*. 1987
4-40	-	Ca	Delpeuch *et al.* 1978
10-14	-	-	Lii and Chang 1978
4-43	Polygonal oval round non-aggregated	-	Bouwkamp 1985
9-38	Non-aggregated, oval polygonal	-	Madamba *et al*. 1975
14.5-20.6			Absar *et al*. 2009
10-14	Round polygonal	A	Takeda *et al*. 1986
10-14	-	Ca	Shiotahi *et al*. 1991

Crystalline structure

The crystalline nature of a starch granule can be by the position of the X-ray diffraction peaks (Zoebel 1988) Hizukuri (1969). Three patterns namely A, B, and an intermediate pattern C, have been found in starch. Hizukuri (1969) demonstrated that mixtures of A- and B-type starches produced intermediate pattern (C-type). Sweet potato starch has a variable X-ray pattern, viz. C (Shin and Ahn 1983; Chiang and Chen 1988; Zoebel 1988), A (Szylit *et al*. 1978; Gallant *et al*. 1982; Takeda *et al*. 1986) or intermediate pattern (Tian *et al*. 1991) in contrast to cereal starches such as wheat and corn which have A-type and potato which has B-type pattern (Zoebel 1988). Takeda *et al*. (1986) found the 'A' pattern for two varieties while it was 'C_A' for another variety with absolute crystallinity of 38%.

Molecular weight

GPC analysis on sweet potato starch has revealed that amylopectin to have peaks at DP =12, DP=8, DP=7, and DP=6. Takeda *et al*. (1986) reported a trimodal pattern for the sweet potato amylopectin while a bimodal distribution has been obtained by Hizukuri (1969). They concluded that sweet potato starch has a higher proportion of 'A' chains and short 'B' chains compared to potato starch. Chain length has been found to vary based on the low viscosity

Table 5 Physico-chemical properties of sweet potato starches.

Properties	Range	Reference
Amylose content (%)	23.2-26.3	Hammett and Berrentin 1961
	29.6-32.4	Madamba *et al*. 1975
	16.1-24.4	Madamba and San Pedro 1976
	17.5-18.3	Delpeuch *et al*. 1979
	13.4-22.5	Shen and Sterling 1981
	22	Watanabe *et al*. 1982
	23.6-27.6	Shin and Ahn 1983
	8.5-17.3	Liu and Liang 1983
	14.8	Liu *et al*. 1985
	17.2-19	Takeda *et al*. 1986
	25-28	Seog *et al*. 1987
	19.4-22.8	Chiang and Chen 1988
	27-38	Martin and Deshpande 1985
	21.5-22	Kitada *et al*. 1988
	22-25	Shiotahi *et al*. 1991
Water binding capacity (%)	178.9-185.5	Shin and Ahn 1983
	66.3-211.6	Seog *et al*. 1987
Swelling volume (ml/g)	46	Woolfe 1992
	27.5-33.3 (95°C)	Chiang and Chen 1988
	24.5-27.4 (85°C)	Seog *et al*. 1987
	63-95 (95°C)	Seog *et al*. 1987
	32-46 (80°C)	Seog *et al*. 1987
Solubility (%)	18	Woolfe 1992
	13.2-14.4 (95°C)	Chiang and Chen 1988
	11.4-12.9 (85°C)	Seog *et al*. 1987
	60-79 (95°C)	Seog *et al.* 1987
	30-50 (80°C)	Seog *et al*. 1987
	15-30 (70°C)	Nuwamanya *et al*. 2011
	38-88 (80°C)	Nuwamanya *et al*. 2011
	69-98 (90°C)	Nuwamanya *et al*. 2011
Digestibility (%)	14.9-43.3	Fuwa *et al*. 1977
	20.8	Ueda and Saha 1983
Acid resistance to 16% sulphuric acid at 50°C	43.7% acid-resistant portion, 49.6% low acid- resistant portion	Nara *et al.* 1983

and high reducing values for some varieties (Woolfe 1992). Sweet potato amylose bears more branches per amylose molecule than that from cassava, potato, wheat or maize, and has a higher molecular weight than maize, wheat and cassava but less than potato amylose. Takeda *et al*. (1986a) suggested this factor as the reason for the low retrogradation tendency of sweet potato amylose. The degree of polymerization and branching influences the physicochemical properties of amylose and amylopectin (Zobel 1988). The alkali number is a measure of the number of reducing end groups and is related to the molecular weight (Schoch 1964). Seog *et al*. (1987) reported alkali number values of six Korean sweet potato starches ranged between 7.66 and 12.13 indicating differences in the molecular weight of starch from different varieties.

Amylose content

The values for amylose content in sweet potato starch have been reported between 8.5 and 35% (**Table 5**). Madamba *et al*. (1975) reported amylose contents of sweet potato starches to be from 29.4-32.2% for six varieties of sweet potatoes from the Philippines. Uehara (1984) found an amylose content of 21.6% while Watanabe *et al*. (1982) reported 20.9%. Garcia and Walter (1998) obtained values ranging from 20-25% for some Peruvian cultivars (by potentiometric titration). The starch extracted from 14 different lines of sweet potato showed similarities in the amylose content as indicated by the narrow range of blue values (0.304-0.339) (Moorthy *et al*. 2010). Curing brought about only minor change on amylose content (Bertoniere *et al*. 1966) or a slight increase (Hammet and Barrentin 1961). In general, sweet potato can have amylose content slightly higher than that of cassava but less than that of wheat, maize or potato (Rickard *et al*. 1991). Delpeuch and Favier (1980) found that the amylose content in sweet potato was not affected by the manner of cultivation or the year of harvest. Collado and Corke (1997) reported that peak viscosity was significantly negatively correlated with amylose content. The amylose content of sweet potato is considered to be one of the most important factors influencing the cooking and textural qualities of storage root and sweet potato starch based products (Collado *et al*. 1999).

Table 6 Physicochemical properties of starches from some selected sweet potato lines.

Sample	Swelling volume (ml/g)	Solubility (%)	clarity	Amylose (Blue value)
ST1	41.25	8.81	Good	0.323
ST2	46.25	10.75	Good	0.313
ST3	37.5	11.25	Good	0.317
ST4	43.75	11.81	Good	0.314
ST5	36.25	8.93	Good	0.304
ST6	33.75	7.29	Good	0.325
ST7	35	13.65	Good	0.314
ST8	43.75	12.94	Good	0.337
ST9	50	9.5	Good	0.315
ST10	40	9.6	Good	0.312
ST11	48.75	7.18	Good	0.325
ST12	37.5	10	Good	0.311
ST13	35	7.15	Good	0.327
ST14	32.5	7.28	Good	0.339

Source: **Moorthy SN, Naskar SK, Shanavas S, Radhika GS, Mukharjee A** (2010) Physico chemical characterization of selected sweet potato cultivars and their starches. *International Journal of Food Properties* **13**, 1280-1298

Swelling and solubility

Swelling power and solubility of starch is an important set of closely related physicochemical property determining the application of starch in different applications. When a suspension of starch is heated, the individual granules swell and a portion of the starch dissolves in the surrounding aqueous medium. The pattern of progressive swelling and solubilisation of different starches have been compared over a range of temperatures to elicit information about the relative strengths of bonding within granules (Rasper 1969). Swelling power and solubility indicates the strength of non-covalent bonding between starch molecules and depend on factors like amylose-amylopectin ratio, chain length and molecular weight distribution, degree of branching and conformation (Schoch 1964; Rickard *et al*. 1991) and are dependent on comparison of relative bond strengths at specific temperatures (Leach *et al*. 1959).

The presence of non carbohydrate substances such as lipid or phosphate in starch may affect swelling (Leach *et al*. 1959; Moorthy and Ramanujan 1986). Swelling power of sweet potato starch varies considerably not only among varieties, but also at different temperatures. The swelling volume and solubility of sweet potato starch was found to be in the range 42-71 ml/g and 25-48% respectively (Moorthy 2002). Delpeuch and Favier (1980) have reported a two stage swelling but Madamba *et al*. (1975) found a single stage swelling for the same starch. The swelling volume for the sweet potato starches from 14 lines was comparatively lower (32.5-50 ml/g) as reported by Moorthy *et al*. (2010) (**Table 6**). Lower swelling of the starch has been attributed to a higher degree of intermolecular association compared to potato and cassava starch.

Solubility of starch depends on a number of factors like its origin, inter-associative forces, swelling power, presence of other components like lipids, surfactants, salts, sugars etc. The high swelling volume of the starch is normally reflected in its solubility. Solubility of sweet potato starch is very similar to cassava starch. It is presumed that the bonding forces might be tenuous but comparatively extensive, immobilizing the starch within the granules even at quite high levels of swelling. Reported solubilities of sweet

potato starch ranged from approximately 10-18% (Madamba *et al*. 1975). Solubility of the different lines of sweet potato ranged from 8.81-13.65% (Moorthy *et al*. 2010). The solubility of four varieties of sweet potato was found to vary between 15 to 98% at a temperature range of 70 to 90°C (Nuwamanya *et al*. 2011).

As reviewed by Tian *et al*. (1991), sweet potato amylose appears to be more branched compared to cassava. Comparative experiments have shown that the swelling and solubility of sweet potato starch are less than those of potato and cassava but generally more than those of maize (Rasper 1969; Delpeuch and Favier 1980). It has therefore been suggested that sweet potato starch has a higher degree of intermolecular association in its starch granules than has potato or cassava starch (Madamba *et al*. 1975).

Water binding capacity

The water binding capacity of sweet potato starch gels, determined by the method of Medcalf and Gilles (1965), ranges from 66.3 to 211.6% as shown in **Table 5**. In general, tuberous starches possess higher water binding capacities than those of cereal origin (Banks and Greenwood 1975), and the majority of workers have demonstrated that sweet potato starch has higher water binding capacity compared to potato (93%) (Dreher and Berry 1983) and cassava starches (72-92%) (Rickard *et al*. 1991).

Digestibility

Starch digestibility by enzymes is of prime importance for evaluating nutritive value and also in industrial applications. For raw starches, digestibility of cassava, sweet potato, *Colocasia*, *Xanthosoma* and *Amorphophallus* starches was quite high (65-75%), comparable to corn starch (76%). Sweet potato starch was found to be very susceptible to degradation by α-amylase and glycoamylase (Cerning-Beroard and Le Dividich 1976). Digestibility of raw starch of 8 sweet potato varieties by glycoamylases has been compared by Noda *et al*. (1992). Gallant *et al*. (1982) found that 'A' type starches showed high susceptibility to α-amylase. They found that pelletisation increased the raw starch digestibility with bacterial α-amylase from 17 to 45%. Scanning electron microscopic studies indicated that enzymatic corrosion takes place mainly at the surface of the granules. The susceptibility of sweet potato starch to α-amylase after 1 day incubation was found to range from 35.7-65.5% for 6 cultivars tested (Absar *et al*. 2009).

Degradation by acid

Dilute acids have been used to elucidate the architecture of the starch granule (Banks and Greenwood 1975). An initial attack on the amorphous regions enhances crystallinity and increases thermal stability (Biliaderis *et al*. 1981). The solubility increases on heating with acid degradation and the viscosity is lowered but granular integrity is maintained even when 25% of the starch has been hydrolysed (Banks and Greenwood 1975). The susceptibility of sweet potato starches to acid corrosion exhibited highly significant differences among cultivars (Rasper 1969).

The kinetics of acid degradation could be described by two exponential hydrolysis rates, a fast hydrolysis of the amorphous regions and a slow hydrolysis of the crystalline regions. Both sweet potato and maize starches had a large amount of acid-resistant starch, but the acid-resistant component of sweet potato starch was hydrolysed at a faster rate than that of other starches.

Degradation by enzymes

Enzymatic degradation can be evaluated by quantitative determination of the products from digestion by GLC/HPLC or by measuring the decrease in hot paste viscosity (Rasper 1969a). Scanning electron microscopy has also been used to examine the starch granules after attack (Hizukuri 1969).

Both amylose and amylopectin are attacked by β-amylase in a step wise manner from the non reducing ends, until cleavage reaches, on average, apposition two residues from the branch points. β-amylase can be used to determine external chain lengths and to estimate the number of branch points (Hokama *et al*. 1980; Lii *et al*. 1987; Manners 1989). Lii *et al*. (1987) reported a β-amylase limit of 87.9% for the amylose of sweet potato starch. In contrast, α-amylase is able to attack the polymers randomly at any α-1:4-linkage that is accessible sterically. Varietal differences among sweet potato starches in susceptibility to attack by α-amylase have been reported to be highly significant (Madamba *et al*. 1975).

Retrogradation

On cooling, dispersions of gelatinized starch granules in water acquire the consistency of gels. Above a critical concentration the swollen granules become entangled in amylose chains which have diffused out of the starch granules. The resultant composite is basically an amylose gel with the swollen starch granules as filler (Gidley 1989). The above situation may be further modified where the starch granules are ruptured by shearing or other methods of thermal or mechanical damage (Mestres *et al*. 1988). Further changes occur on storage, involving recrystallisation (or retrogradation) of the polymer chains. Retrogradation is influenced by amylose amylopectin ratio, the presence of other foreign molecule such as sugars, salts and emulsifiers, molecular size, temperature, pH and other non-starch components (Del Rosario and Pontiveros 1983).

Takeda *et al.* (1986) found that the retrogradation of sweet potato amylose appeared to occur at the same rate as that of cassava but more slowly than that of Irish potato amylose. In contrast, Rasper (1969) reported that sweet potato amylose retrograded slower than that of cassava and also that sweet potato amylopectin retrograded at a faster rate than cassava amylopectin. Del Rosario and Pontiveros (1983) found that sweet potato starch retrograded more slowly than wheat, corn and cassava starches and attributed this fact as the reason for the observation that bread containing sweet potato flour as a substituent staled at a slower rate than other breads. Retrogradation is usually accompanied by gel hardening and by leakage of water from starch gel during storage. Retrogradation properties of tuber and root starches have been investigated by DSC, rheological measurements, FTIR, Raman spectroscopy and X-ray diffraction. However, most of the available are on potato and cassava starches (Hoover 2001).

Sol stability

Sol stability or paste stability reflects the retrogradation tendency of starch pastes. Cassava and sweet potato starches have low retrogradation tendency and therefore exhibit high paste stability which is a useful property in foods which require long term storage, especially subjected to repeated cooling and thawing operation.

Thermal characteristics

Differential Scanning Calorimetry (DSC) is an important tool to study starch gelatinisation (Biliaderis 1983; Biliaderis 1990; Eliasson 1994; John and Shastri 1998). DSC studies have been primarily carried out on cereal starches and to a little extent on potato and cassava starches (Stevens and Elton 1971; Wootton and Bamunuarachchi 1979; Asaoka *et al.* 1992; Moorthy *et al*. 1996; Defloor *et al*. 1998; Farhat *et al*. 1999) whereas information on the DSC of the other root starches is comparatively scanty. As starch grains are heated in aqueous suspension, they imbibe large quantity water. At least three main stages, hydration, swelling and melting of the crystallites occur during the process

Table 7 Thermal properties of sweet potato starch.

T onset (°C)	T peak (°C)	T endset (°C)	ΔH (J/g)	Reference
67-75	73-79	81.4-84.8	10-12.3	Chiang and Chen 1988
65.6-68.2	72.8-74.3	84.6-86.8	15.1-16.3	Kitada *et al*. 1988
61.3	70.2-77	80.7-88.5	15.1-16.3	Collado *et al*. 1999
58-64	63-74	78-83	14.8-18.6	Wankhede and Sajjan 1981
67.3	72.7	79.6	13.6	Valetudie *et al*. 1995

Table 8 Differential scanning calorimetric characteristics of the hydrothermic transition of purified starches and fresh and freeze dried tubers.

Item	T onset (°C)	T peak (°C)	T endset (°C)	ΔH (J/g)
Starch	67.3	72.7	79.6	13.6
Fresh tubers	67.4	73.5	80.1	6.8
Freeze-dried tubers	67.8	73.2	81.5	9.3
Small starch granules	75.6	82.6	88.3	15.3

Source: **Valetudie JC, Colonna P, Bouchet B, Gallant DJ** (1995) Gelatinisation of sweet potato, tannia and yam starches. *Starch/Stärke* **47**, 298-306

Table 9 Gelatinization properties of sweet potato flours.

Varieties	Gelatinization temperatures, °C			Enthalpy, J/g	Gelatinization temperature range, °C	Peak Height Index, J/g
	Onset	Peak	End set			
SI 60	80.81 ± 0.03 ab	83.91 ± 0.16 ab	88.04 ± 0.14 a	9.02 ± 0.37 b	7.23 ± 0.17 b	2.90 ± 0.30 a
SV 280	79.79 ± 0.62 ab	83.19 ± 0.71 a	89.31 ± 0.49 ab	9.44 ± 0.29 b	9.51 ± 1.10 ab	2.78 ± 0.16 ab
CO3-4	79.29 ± 0.51 a	83.65 ± 0.85 ab	88.04 ± 0.11 a	9.31 ± 0.49 b	8.75 ± 0.62 ab	2.13 ± 0.28 bcd
Sree Arun	82.80 ± 1.38 c	86.77 ± 0.73 c	92.62 ± 1.39 c	9.41 ± 0.19 b	9.83 ± 2.76 ab	2.37 ± 0.44 abc
Sree Varun	81.18 ± 0.31 b	84.90 ± 0.21 b	89.57 ± 0.25 ab	9.27 ± 0.54 b	8.39 ± 0.64 ab	2.49 ± 0.26 ab
362-7	79.27 ± 0.39 a	84.39 ± 0.09 ab	90.87 ± 0.93 b	7.68 ± 0.22 a	11.61 ± 1.32 a	1.50 ± 0.10d
SV 98	80.15 ± 0.44 ab	84.69 ± 1.01 ab	90.75 ± 0.62 b	7.52 ± 0.75 a	10.60 ± 0.17 a	1.65 ± 0.38cd

Source: **Sajeev MS, Sreekumar J, Vimala B, Moorthy SN, Jyothi AN** (2012) Textural and gelatinization characteristics of white, cream and orange fleshed sweet potato tubers (*Ipomoea batatas* L.). *International Journal of Food Properties* **15 (4)**, 912-931

(Blanshard 1979).

Gelatinisation temperature is indicative of the temperature at which the starch granules begin gelatinising. The gelatinization temperature is controlled not only by the water content but also by the presence of various extraneous chemicals, salts, sugars and other small molecules. Gelatinization onset (To), peak (Tp) and conclusion (Tc) temperatures and enthalpy of gelatinization (ΔH) are obtained from the thermograms. Gelatinization temperature range is calculated as the difference between Tc and To. Peak height index is measured as the ratio of the enthalpy to the difference between Tp and To.

Average gelatinization temperature for starch from 6 cultivars of sweet potatoes was obtained in the range from 63.6-70.7°C by Madamba *et al*. (1975). A significant positive correlation was observed between average gelatinization temperature and amylose content of the starches. Gelatinisation occurred over a range of 12-17°C. Barham *et al*. (1946) found that five cultivars had average gelatinization temperatures from 69-75.5°C and that the average gelatinization temperature was lowered on curing the roots (**Table 7**). Rasper (1969) reported that sweet potato starch began to gelatinize at 77°C and continued the increase in viscosity until a temperature of 85°C was attained. Collado *et al*. (1999) obtained considerable variation in all the DSC parameters of 44 sweet potato varieties. The mean T_{onset} was 64.6°C and range 61.3-70°C, mean T_{peak} 73.9°C (range 70.2-77°C) and mean T_{end} 84.6°C, range being 80.7-88.5°C and the mean gelatinisation range was 20.1°C with a range of 16.1 to 23°C. Garcia and Walter (1998) found the range to be between 58-64°C for T_{onset}, 63-74°C for T_{peak} and 78-83°C for T_{end} for the two varieties cultivated at different locations. While selection index did not affect the values, location influenced the parameters (Tian *et al*. 1991). Noda *et al*. (1996) did not observe any effect of fertilisation on the DSC characteristics of two sweet potato varieties. During growth period, the T_{onset} was the lowest at the latest stage of development. Kitada *et al*. (1988) found that the gelatinization temperatures were affected by the geographical region in which the sweet potatoes had been grown. Noda *et al*. (1998) reported that To, Tp, ΔH of 51 sweet potato starches differing in variety or cultivation conditions ranged between 55.7-73.1°C, 61.3-77.6°C and 12.7-16.8 J/g respectively. Noda *et al*. (1998, 1995) found that only small variations in chain length distributions (DP6-17) of amylopectin deter-mined by HPAEC were observed in 31 varieties and 51 samples of sweet potato starches. The enthalpy values of 11 different genotypes of sweet potato varied from 7.6 to 13.2 J/g (Zhu *et al*. 2011). They reported that increase in short outer chains of amylopectin reduced the packing efficiency of double helices within the crystalline region, resulting in lower gelatinization temperature and enthalpy. Valetudie *et al*. (1995) have compared the gelatinization temperatures of starch from fresh tubers and freeze dried tubers of sweet potato (**Table 8**).

Swelling is controlled by the strength of the internal structure of the granule. Granule size, amylose content, molecular weight, crystallinity and the internal granular organization all affect gelatinization characteristics (Banks and Greenwood 1975). Higher amylose content has also been reported to increase the gelatinization temperature (Takeda and Hizukuri 1974; Madamba *et al*. 1975). Starch gelatinization may be explained either in structural term as a loss of macromolecular organization and order or as a swelling process which also brings about major rheological effects.

Gelatinisation enthalpy depends on a number of factors like degree of crystallinity, intermolecular bonding, amylose content etc. For sweet potato starch, the reported values for gelatinisation enthalpy lie between 10-18.6 J/g (Tian *et al*. 1991; Garcia and Walter 1998; Collado *et al*. 1999). Effect of variety and environmental conditions was also evident (Garcia and Walter 1998; Noda *et al*. 1996). During growth period, the ΔH was lowest at the earliest stage of development in two sweet potato cultivars and the enthalpy ranged between 11.8-13.4 J/g (Noda *et al*. 1992).

Among the DSC gelatinization parameters of flours from different sweet potato varieties viz., CO3-4, SV 280, SI60, Sree Arun, Sree Varun, 362-7 and SV 98; Sree Arun recorded the highest values for all the parameters (i.e. T_o-82.80°C, T_p-86.77°C, T_e-92.62°C, ΔH-9.41 J/g) whereas lowest onset (79.27°C) for 362-7, peak (83.19°C) for SV280 and end set (88.04°C) for CO3-4 and SI60 and enthalpy (7.52 J/g) for SV98 (**Table 9**) (Sajeev *et al*. 2011). There was a clear cut difference among the two groups of varieties as far as enthalpies of gelatinization are concerned.

For cream fleshed varieties, the values hovered around 9.23 J/g whereas for orange fleshed, the values were 7.68 and 7.52 J/g. It is worth noting that for orange fleshed varieties, the enthalpy was much lower (mean 7.60 J/g) than that of the white fleshed varieties (9.29 J/g). However, among the two orange fleshed varieties, the values of gelatinization temperature were almost same except for T_o, for which the range was 79.27 to 80.15°C. Collado *et al.* (1999) in their studies on the genetic variation in the physico-chemical properties of sweet potato starch from 44 genotypes observed a wide variability in the DSC gelatinization parameters and suggested that starch differing in gelatinization temperature and enthalpy have different cooking characteristics.

Variation in starch gelatinization properties measured by DSC is also due to the differences in molecular structure of amylopectin within the same botanical origin of sweet potato. The starches with lower T_o, T_p and ΔH were shown to have higher content of extremely short chains with D6 and 7 in amylopectin molecules and amylose/amylopectin ratio did not have an impact on DSC parameters. A negative correlation of molar percentage of DP6 and DP7 with T_o, T_p and ΔH values was also observed.

Table 10 Rheological properties of starch extracted from selected sweet potato lines.

Lines	Peak viscosity	Breakdown	Final viscosity	Setback	Pasting temp (°C)
	cP				
ST1	2924	1450	2098	800	68.70
ST2	3467	2246	3677	1317.5	67.48
ST3	3475	1306	3212	1182	67.85
ST4	3376	1997	4153	1683.5	65.9
ST5	3557	1069	3250	945	67.80
ST6	3714	2190	4076	1076	75.85
ST7	3498	1392	4334	1207	77.50
ST8	3902	1080	3702	872	76.50
ST9	3123	2541	2766.5	762.5	70.2
ST10	3602	1940	3031	871	70.7
ST11	3583	1484	4530	1426	75.90
ST12	3536	1571	3087	1034	71.85
ST13	4729	2092	3838	1201	68.65
ST14	3560	2180	3534	1154	70.2

Source: Moorthy SN, Naskar SK, Shanavas S, Radhika GS, Mukharjee A (2010) Physico chemical characterization of selected sweet potato cultivars and their starches. *International Journal of Food Properties* **13**, 1280-1298

Rheological properties

Sweet potato starch and flour are prominent ingredients in many of the traditional food preparations and industrial products and hence their physico-chemical and functional properties are very much important for their selection for various applications. Exhaustive literature is available on the pasting properties of sweet potato starch and their genotypic variation. New sweet potato lines having 10-20°C lower pasting temperature compared to normal values have been reported by Katayama *et al*. (2004). Jangchud *et al*. (2003) observed starch pasting temperature of 80.5°C for orange fleshed and 74.8°C for purple fleshed tubers. Genotypic variation of pasting profile as studied by Collado *et al*. (1999) on 44 genotypes showed type A profile at 11% starch concentration and Type C profile at 7% starch concentration. As sweet potato flour is an important ingredient in formulated food system, its functional and pasting properties also need attention. Physico-chemical properties of sweet potato flour were studied by Osundhahunsi *et al*. (2003) and flour characteristics of sweet potato prepared by different drying techniques by Yadav *et al*. (2006).

The intrinsic viscosity is related to the ability of polymer molecules to increase the viscosity of the solvent, in the absence of any intermolecular interactions (Young 1981). Intrinsic viscosity is directly related to molecular size and therefore to the degree of polymerization. The use of a lower concentration of starch would result in a general lowering of the paste viscosities and the softening of peaks and breakdown because of reduced friction due to presence of lesser number of swollen granules (Collado *et al*. 1999). Several studies found that sweet potato starch does not show a peak viscosity at 4-6% (w/v) (Tian *et al*. 1991). However, Lii and Chang (1978) reported a moderate peak and a high set back on cooling with at a starch concentration of 7%.

Varietal differences on viscosity values have been reported as significant (Madamba *et al.* 1975; Liu *et al*. 1985). Sweet potato amylose has a limiting viscosity higher than that of wheat but lower than that of cassava or Irish potato amylose (Takeda *et al*. 1974, 1986). Similarly, sweet potato amylopectin has a lower limiting viscosity number than Irish potato amylopectin, suggesting smaller or more spherical molecules (Suzuki *et al*. 1985; Takeda *et al*. 1986). Since the peak viscosity value indicates how readily the starch granules are disintegrated, cohesive forces within the granules having higher values are stronger than those having lower values. Breakdown viscosity which indicates the consistency of the paste after holding at 93°C for 15 min provides an estimate of the resistance of the paste to disintegration in response to heating and stirring. Setback defined as the difference between the breakdown viscosity and the viscosity at 50°C has been directly related to the amount of amylose leached from the granule (Greenwood 1979).

Most of the starches extracted from 14 different lines of cassava had excellent viscosity properties (Moorthy *et al*. 2010) (**Table 10**) and possessed viscosity greater than 3000 cP. The starch isolated from variety ST-13 variety rich in anthocyanin content had high peak viscosity. Thus this variety promises both as food and in starch production with good starch quality. The breakdown is slightly lower compared to cassava starch showing that the granules are stronger for sweet potato starch.

In a study conducted by Sajeev *et al*. (2011) on the viscosity properties of sweet potato flour from different varieties, all the viscosity parameters were significantly different among the varieties ($P < 0.05$) (**Table 11**). Flour from the tubers of Sree Arun recorded the minimum value of trough (407 cP), final (553 cP) and setback (146 cP) viscosities and maximum pasting temperature (82.73°C), whereas peak viscosity was minimum for Sree Varun (617 cP) and breakdown for SI 60 (100 cP). However, CO3-4 recorded highest value of peak (940 cP), trough (738 cP), final (955 cP) and setback (217 cP) and minimum pasting temperature (79.75°C). Except for the setback viscosity and pasting temperature, the orange-fleshed varieties had significant difference in their values. Setback ratio is used to predict the retrogradation tendency of starchy materials, which did not vary much and ranged from 1.29 to 1.37 only.

Differences in the viscometric properties have been attributed to the genetic make up and structural variation of the starch present in the tubers. Variation in the associated forces in the starch granules can be responsible for the observed difference in the pasting properties of different varieties. (Moorthy *et al.* 1996) Besides, the varied quantity of starch in the flour also contributed to the difference in pasting properties, but no regular trend between starch content and pasting parameters could be observed. Hence the contribution of sugar or fibre individually or their combined affect and ratio of the amylose/amylopectin content in the starch may be responsible for the reported changes in pasting properties of sweet potato flour.

The rheological properties of sweet potato starch have been examined in detail. During heating, the storage modulus (G') and loss moduli (G") increased while phase angle decreased indicating change from sol to gel. The initial increase in G' and G" has been attributed to progressive swelling of starch granules leading to close packing. When the starch granules became very soft, deformable and compressible, decrease has been observed. Most of the reported values for G' and G" refer to starch pastes that have been

Table 11 Pasting properties of sweet potato flours.

Varieties	Viscosity parameters						Pasting
	Peak, cP	Trough, cP	Break down, cP	Final, cP	Set back, cP	Set back ratio	temperature, °C
SI 60	721.5 ± 4.95 b	621.5 ± 2.12 e	100 ± 2.83 a	822 ± 2.12 e	200 ± 0 cd	1.32 ± 0 ab	80.25 ± 0.42 a
SV 280	843 ± 14.14 c	576 ± 11.32 d	267 ± 2.83 e	775 ± 26.16 d	199 ± 14.9 cd	1.35 ± 0.02 ab	80.38 ± 0.81 a
CO3-4	940 ± 24.04 d	738 ± 7.07 f	202 ± 16.97 c	955 ± 11.32 f	217 ± 4.24 d	1.29 ± 0 b	79.75 ± 0 a
Sree Arun	647 ± 26.69 a	407 ± 3.54 a	241 ± 26.16 de	553 ± 23.33 a	146 ± 19.8 a	1.36 ± 0.05 a	82.73 ± 1.67 b
Sree Varun	617 ± 5.65 a	454 ± 1.41 b	163 ± 7.07 b	620 ± 7.07 b	166 ± 8.5 ab	1.37 ± 0.02 a	81.03 ± 0.60 ab
362-7	821 ± 9.19 c	563 ± 5.66 d	258 ± 14.85 e	748 ± 3.53 d	185 ± 9.2 bc	1.33 ± 0.02 ab	79.83 ± 1.03 a
SV 98	727 ± 7.78 b	512 ± 7.78 c	215 ± 0 cd	688 ± 6.36 c	176 ± 1.4 bc	1.34 ± 0.01 ab	81.09 ± 0.62 ab

Source: **Sajeev MS, Sreekumar J, Vimala B, Moorthy SN, Jyothi AN** (2012) Textural and gelatinization characteristics of white, cream and orange fleshed sweet potato tubers (*Ipomoea batatas* L.). *International Journal of Food Properties* **15 (4)**, 912-931

held at room temperature for several hours after heating.

Sweet potato starch behaves almost similar to cassava starch in all its viscosity characters. In a study of 44 different sweet potato genotypes using Rapid Visco Analyser, Collado *et al*. (1999) have worked out the correlations among the RVA parameters. They observed wide variation not only in the peak viscosity but also on broadness of peak. The rheological properties of sweet potato starch extracted using an enzymatic process did not vary among the different concentrations of enzyme (Moorthy and Balagopalan 1999).

Pasting temperature

The consistency of the paste, the properties of the gel and the latter's viscosity during the pasting cycle are important in many industrial applications as they impart important quality characteristics (Leelavathi *et al*. 1987).

The pasting temperature of sweet potato starch varies between 62-86°C (Tian *et al*. 1991; Collado and Corke 1997; Kitahara *et al*. 1999). The pasting temperature of sweet potato starch obtained using Brabender Viscograph varied between 66.0 and 86.3°C while microscopic determination provides values between 57-70 to 70-90°C. Noda *et al*. (1996) observed the pasting temperatures of starch from two sweet potato cultivars grown at different fertiliser levels to be 70.8-73.9°C. Starch pasting properties influence sweet potato eating quality and noodle quality and also are directly responsible for starch industrial uses (Collado *et al.* 1999).

MODIFICATION OF SWEET POTATO STARCH BY HEAT MOISTURE TREATMENT

Heat treatment is a physical method of modification of the starch properties. Heat moisture treatment studies were conducted by Jyothi *et al*. (2010) by varying the starch moisture content from 15 to 20%, temperature from 80 to 120°C and time from 6 to 14 h. The crystallinity of the starch increased due to the treatment as indicated by the increase in intensity of the XRD peaks. The swelling volume of the treated starch was decreased due to the increase in temperature, moisture and time whereas solubility increased with increase in duration of heat moisture treatment. The significant reduction in viscosity breakdown and setback viscosity of the treated starch showed the better paste stability. For the samples heat moisture treated at the lowest temperature of 80°C, the gelatinization temperature range decreased whereas enthalpy values increased. The pastes of heat moisture treated starch exhibited higher storage modulus than that of the loss modulus showing more of a solid like behavior. There was a significant decrease in phase angle also for the treated starches, which is also an indication of the more solid like nature of the pastes.

CONCLUSION

Sweet potato is one of the world's most important starch producing crops, with 95% of all tubers produced in Asia and Africa. Sweet potato is used as direct food, processed foods, industrial starch and animal feed. The utility of sweet potato starch is primarily determined by its physicochemical properties, which are mainly by the amylose/amylopectin ratio, the molecular structure, granule size and inorganic constituents of starch. Pasting properties also influence the quality of food processing materials and industrial products. Being a nontraditional source of starch, the characterization of genetic variation and interrelationships of physical properties of sweet potato starch that can guide utilization is therefore essential. An awareness of their potential uses can help in large scale cultivation of these crops and extraction of starch from them. It is also possible to modify the starch properties by simple physical methods like hydro thermal or steam-pressure treatments. Latest developments in biotechnology can also be employed to modify the starches. These include fermentation of starch by the use of selective organism or enzymatic modification, which can bring about specific changes in functional properties. Now-a-days research is being carried out to produce new cultivars and breeding materials with distinctive amylose content and pasting properties. Sweet potato having higher starch yield and low gelatinization temperature may be effective for reducing the production costs of various end products. The various improvements in starch properties are useful for providing consumers with starch products and enhancing the demand for sweet potato starch.

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