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Physico-chemical properties of flours and starches from selected commercial tubers available in Australia

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Abstract: Physico-chemical properties of flours and starches extracted from the tubers, taro, yam, and sweet potato commercially available in Australia were investigated. Results pointed out that each of the different tubers might be utilized for specific applications in food processing. In contrast to the sweet potato and yam flours and starches, with larger particle size distributions from 28.3 and 251 µm, the taro flour with a mean particle distribution size from 1.067-64.19 µm is better suited in applications where improved binding and reduced breakability is required. Paste clarity of the sweet potato was above 30% light transmittance whereas the other two tubers (yam and taro) had less than 10% light transmittance in both cases. All flours and starches exhibited variable pasting behavior, with starches having a higher viscosity. Among flours, taro had the highest peak and final viscosity. Yam flour and starch were more stable against heat and mechanical treatment. The extracted mucilage from these tubers showed apparent shear thinning behavior. Concentration dependant flow behavior of all mucilage samples was successfully fitted by the Power Law (Ostwald), Hershel Buckley and Casson models.

Keywords: Physico-chemical properties, taro, yam, sweet potato, flour, starch

Introduction

Tubers and roots are important sources of carbohydrates as an energy source and are used as staple foods in tropical and sub tropical countries (Liu *et al*., 2006). These products have nutritionally beneficial components, such as a resistant starch and mucilage. Resistant starch has been attributed with a slow digestion in the lower parts of the human gastrointestinal tract which results in the slow liberation and absorption of glucose and aids in the reduction of the risk of obesity, diabetes and other related diseases (Liu *et al*., 2006). Whereas mucilage extracted from various tubers and roots has been reported to possess angiotensin converting enzyme inhibitory (Lee *et al*., 2003) and antioxidative activities (Nagai *et al*., 2006). Also tubers and roots do not contain any gluten, which is an important factor when considering a carbohydrate source. Using tubers as a source of carbohydrate instead of gluten containing carbohydrates, may aid in a reduction in the incidence of celiac disease (CD) or other allergic reactions (Rekha and Padmaja, 2002). With these benefits in mind an examination of the physicochemical properties of some representative tubers and roots was undertaken. The food industry utilises some tubers and roots for their flour and starch products and literature reports on the uses of such. However upon examination of available literature, it is evident that very little physiochemical characterization of these tubers' starches, flours and mucilage has been undertaken. Such an examination may demonstrate further potential uses within the food industry for the replacement of more traditional forms of carbohydrates or to produce entirely new food products. Therefore, the present study was aimed to assess the physicochemical and functional properties of the main components of some starchy tubers commercially produced in Australia, in an attempt to broaden what applications they may be used for within the food industry. The tubers assessed in this study were sweet potato, yam and taro. These tubers were sourced from Queensland (Australia) from local producers and harvested in March 2007. They have been analyzed in this study with the understanding that they are a representative samples

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from one harvest only and that all results contained in this report are for a preliminary examination into the properties of these products and that. For a more conclusive study further examination of various samples from different regions, seasons and sites would need to be examined.

Materials and Methods

Materials

Matured tubers of taro (*Colocasia esculenta var. antiquorum*), yam (*Dioscorea alata*) and sweet potato (*Ipomoea batatas* var. Beauregard) were assessed in this study. Received tubers were harvested in March 2007 and were of a uniform medium size and free from mechanical or pathological injuries.

Sample preparation

Flour extraction

Flour extraction was conducted following an established procedure (Alves *et al*., 2002). The tubers were peeled, washed, cut into 1-2 cm cubes, and sliced into thick chips (~5mm). These chips were then soaked in sodium metabisulfit (0.075%) for ~5 min and oven dried at 30°C for 40 hours until they reached ~13% moisture. Subsequently, the dried chips were milled into flour and sifted through a 300-µm sieve. The flour was then packed into a closed container and stored under dry conditions at room temperature until used for further applications.

Mucilage separation

The mucilage concentrate was prepared following the method as described by Jiang and Ramsden (1999). The flour sample (100 g) was dispersed in 300 ml of sodium metabisulfit (0.075%) and stored at 4°C overnight. This dispersion was centrifuged (Sorvall RC 5, Beckman, MN, USA) at 14,000 *x g* for 20 min and the supernatant (mucilage) was collected. This was followed by pellet dissolution in metabisulfit solution and centrifugation under conditions as described above. The resulting supernatant was filtered using a filter paper (110 mm, Advantec) and freeze dried (Dynavac freeze drier; Dynavac Eng. Pty. Ltd., Melbourne, Australia).

Starch isolation

The pellets obtained from the centrifugation step during the mucilage separation were resuspended in a large amount of sodium metabisulfit (0.075%), and centrifuged (14,000 *x g*; 20 min, Sorvall). This step was repeated until the supernatant layer was almost colorless. The supernatant was decanted and sodium hydroxide (0.1 M) was added to the remaining sediment. This was followed by addition of deionized water to wash the pellets until their pH was neutral. The recovered starch was dried using an air oven at ~35°C for 30h, ground, sieved using a 250 µm sieve and stored in an air tight container under dry conditions.

Proximate analysis of extracted components

All extracted components were assessed for moisture and protein content in accordance with the AACC methods (standards #44-15A and 46-12, respectively (AACC, 2000). Total amylose content was determined using colorimetric method after removal of lipids from flours and starches with hot 75% n-propanol for 7 hours in a Soxhlet extractor (Hoover and Ratnayake, 2005). The pure potato amylose (Sigma) and corn amylopectin (0-100% amylase, Sigma) were used to create a standard curve. Subsequently, the total amylose content of each sample was inferred from this standard curve. Amylopectin content was determined by the difference. Total starch was measured using total starch assay kit (Megazyme, Ireland). The resistant starch and non-resistant starch were determined using a Megazyme resistant starch assay kit (Megazyme, Ireland). The digestibility was determined based on the ratio of non-resistant starch to the total amount of resistant and non-resistant starch (Liu *et al*., 2006).

Particle size distribution

The particle size distributions of flour and starch samples were measured using a particle size analyzer (Coulter LS130, Coulter Corporation, FL, USA). Before the measurement, the background reading for water was recorded and each sample was added until an obscuration of 18-20% was achieved. This was followed by sonication for 5 min to disperse any agglomerates.

Swelling volume

The swelling volume of flour and starch samples was measured according to Santacruz *et al* (2003). Briefly, 0.5% flour and starch suspensions were prepared in 15 mL Falcon tubes and heated in a water bath at 50, 60, 70, 80, 90 or 100°C for 30 min with constant agitation to avoid sedimentation. This was followed by centrifugation (Sorvall) at 1000 x g for 15 min at 20°C. The sedimented fraction was weighed and its mass related to the mass of dry starch was expressed as swelling power (w/w).

Paste clarity

The paste clarity was determined by measuring the light transmittance (%) according to Craig *et al.*

(1989). The flour and starch dispersions (1%) were prepared in a screw cap tube and heated at 100°C for 30 min with intermittent mixing. The tubes were then cooled down and stored at 4°C for 7 days. To monitor the tendency for retrogradation, the percentage of light transmittance was measured at 650 nm each day against the water blank using a spectrophotometer (Cary IE; Varian Australia Pty. Ltd., Melbourne, Australia).

Pasting properties

Pasting properties were determined using a starch cell (Physica Smart, Starch analyzer-Anton Paar) attached to a CR/CS rheometer (MCR 301, Anton Paar, GmbH, Germany) and established methodology (Jayakody *et al*., 2007). A sample (7% w/w) was equilibrated at 50°C for 1 min, then heated from 50 to 95°C at 6°C/min, held at 95°C for 5 min, cooled to 50°C at 6°C/min, and held at 50°C for 2 min. The speed was 960 rpm for the first 10s, then 160 rpm for the reminder of the experiment. The pasting properties of each sample were inferred from acquired diagrams including the peak time, peak viscosity, holding strength, setback, and final viscosity.

Thermal properties of flours and starches

The thermal properties of the flours and starches were assessed using differential scanning calorimetry (DSC-7, Perkin Elmer, Norwalk, CT, USA). Deionized water (11 µl) was added to 3 mg of sample in an aluminum pan, which then was allowed to stand for 2 h at room temperature before analysis to ensure the equilibration of sample and water. The sample was heated from 20 to 120°C with 10°C/min heating rate. An empty aluminum pan was used as a reference in each measurement. From this experiment, the onset (T_o), peak (T_p), and conclusion (T_c) temperature, as well as gelatinization enthalpy (ΔH) were reported (Ratnayake *et al*., 2001).

Rheological properties of mucilage

Mucilage suspensions were prepared at different concentrations (2.5; 5; or 10% w/w) by adding the appropriate quantity of freeze-dried powder to deionized water. All suspensions were kept overnight to allow for complete hydration. All samples were subjected to a shear rate sweep at 20°C, from 0.01 to 100 s^{-1} in a plate and cone geometry (50 mm diameter, 1°) of the rheometer (Anton Paar), also equipped with a temperature and moisture regulating hood. The temperature was controlled with a Peltier system (Anton Paar). The data of all rheological measurements were analyzed with the supporting software Rheoplus/322 v2.81 (Anton Paar). The flow curves were fitted to several rheological models: Ostwald (Power Law), Herschel-Buckley and Casson models:

Ostwald (Power law) model: $\eta = K \cdot \dot{\gamma}^{n-1}$

Herschel-Buckley model: $\sigma = \sigma_0 + K' \cdot \dot{\gamma}^{n'}$

Casson models: $\sigma^{0.5} = \mathbf{K_{0c}} + \mathbf{K_c} \cdot \dot{\gamma}^{0.5}$

In which η is the apparent viscosity (Pa s); K and K' are consistency index (Pa s^n); n and n' are the flow behavior index; $\dot{\gamma}$ is the shear rate (1/s); and σ_o and σ present yield and shear stress, respectively (Pa). Casson yield stress (σ_{oc}) was determined as the square of the intercept (K_{oc}) and consistency coefficient (K_c) was obtained from linear regression of the square roots of shear rate–shear stress data.

Statistical analysis

A randomized block design was applied with tubers and replications (block) as the main effects. This block structure was repeated at least three times with at least 2 sub samplings. Results were analyzed using a General Linear Model (SAS, 1996). The level of significance was present at $p<0.05$.

Results and Discussion

Physicochemical properties: starch and flour

Proximate analysis

Total starch

The chemical composition of flours and starches extracted from the samples analysed is presented in Table 1. Each species examined had different compositions. The total starch (TS) content of taro and yam flours was comparable ($p>0.05$; 80.1% and 78.1%, respectively); however, these were significantly ($p<0.05$) higher than that of sweet potato flour (65%). Examination of literature revealed TS contents for all three at higher levels so further purification of all samples was conducted and the TS was reanalyzed resulting in values comparable to literature.

Amylose

The total amylose content was very low in the taro samples (5.59%) while yam and sweet potato contained comparable concentrations (14.60% & 18.12%) (Table 1). These observations were in agreement with previous reports (Srichuwong *et al*., 2005b, Hung and Morita, 2005).

Table 1. Chemical composition of flours, starches, and mucilage extracted from taro, yam and sweet potato tubers

Source	Protein (%)	Total Starch (%)	Amylose (%)	Amylopectin (%)	Moisture (%)
Flours					
Taro	6.28±0.07^{b}	80.95±0.5^{a}	5.59±1.54^{c}	94.41±2.96^{a}	8.19±0.07^{b}
Yam	10.46±0.11^{a}	78.83±1.99^{b}	14.60±1.19^{b}	85.40±1.74^{b}	10.51±0.82^{a}
Sweet potato	3.15±0.10^{c}	65.05±1.8^{c}	18.12±0.97^{a}	81.88±1.30^{b}	7.07±0.17^{b}
Starch					
Taro	1.31±0.00^{b}	88.66±1.86^{a}	14.45±1.54^{c}	85.55±1.27^{a}	8.99±0.19^{b}
Yam	3.23±0.01^{a}	81.72±2.05^{c}	31.33±1.47^{a}	68.67±0.85^{c}	11.16±0.28^{a}
Sweet potato	0.61±0.00^{c}	84.15±2.68^{b}	28.69±1.04^{b}	71.31±1.63^{b}	9.96±0.35^{b}
Mucilage					
Taro	13.5±0.15^{b}	n.dt	n.d	n.d	16.10±0.04^{a}
Yam	23.48±0.14^{a}	n.dt	n.d	n.d	17.53±0.39^{a}
Sweet potato	7.66±0.14^{c}	n.dt	n.d	n.d	11.10±0.18^{a}

All data reported on dry basis and represent the mean of three replicates.
Values followed by the different superscript in each column are significantly different ($P<0.05$).
n.d = not detected
n.dt = not determined

Protein content

Among the flour samples, yam had the highest % protein content with 10.46% and taro 6.28% whilst sweet potato had the lowest value of 3.15%. The starches for each species as expected had reduced protein contents with the yam starch containing the highest amount of protein (3.23%) followed by the taro (1.31%) and the sweet potato (0.61%). In general the process used in this study showed that the protein content for all the starches tested was higher than those that have been reported in literature i.e.: 0.10-0.5% for yam starch (Gebre-Mariam *et al*., 1998, Alves *et al*., 2002, Freitas *et al*., 2004), 0.9-1.3% for taro starch (Tattiyakul *et al*., 2006) and 0.14-0.23% for sweet potato starch (Chen *et al*., 2003b). However due to the samples not being exactly the same differences in results were not unexpected.

Resistant starch, non resistant starch and digestibility

As can be seen in table 2 there are significant differences in the results for each of the samples tested. Among the flour samples, taro contained the highest amount of RS (35.19%) followed by yam with (22.48%) and sweet potato with the lowest concentration of only (0.97%). As expected, the levels of NRS were inversely related to RS content with sweet potato flour containing the highest amount. Also shown is a relationship between RS content and the degree of digestibility of the samples (Table 2). Particularly with the starch samples, with the sweet potato starch showing the highest degree of digestibility with the lowest % content of RS. These results also show that in general, the content of RS in taro and yam was higher than that of selected cereals including rice (0.6%), wheat (0.6%), or buckwheat (0.8%) (Liu *et al*., 2006).

The structure of the starch in these species of tuber may also account for the differences in the degree of digestibility. It has been shown in previous studies that an A-type X-ray diffraction starch, that has a high proportion of short branch chain amylopectin, has inferior crystallinity and thus is more susceptible to digestion by α-amylase compared to its opposite, B-type starch (Jane *et al*., 1997). Sweet potato and taro starches have been reported to have an A-type

Table 2. The content of resistant and non resistant starch and digestibility of flours and starches extracted from taro, yam, and sweet potato tubers

Source	Resistant starch (%)	Non-resistant starch (%)	Digestibility (%)
Flours			
Taro	35.19±3.92^{a}	35.73±2.96^{b}	50.42±2.90^{b}
Yam	22.48±2.33^{b}	18.85±0.08^{c}	45.72±2.76^{b}
Sweet potato	0.97±0.35^{c}	75.55±8.95^{a}	98.74±0.43^{a}
Starch			
Taro	44.98±5.50^{b}	47.05±2.68^{b}	51.22±4.47^{b}
Yam	68.50±8.82^{a}	13.48±7.09^{c}	16.55±9.05^{c}
Sweet potato	0.92±0.61^{c}	85.78±7.70^{a}	98.95±0.63^{a}

All data reported on dry basis and represent the mean of three independent replications. Values followed by the different superscript in each column are not significantly different ($P<0.05$).

X-ray diffraction (Srichuwong *et al*., 2005a) and had higher digestibility compared to yam starch that has a B-type X-ray diffraction (Srichuwong *et al*., 2005a).

The significance of these factors is in relation to the use of starches for food product manufacturing. The choice of starch may have significant effects especially in relation to produced food products having health benefits. As has been discussed previously in this study lower digestibility (related to higher percentages of RS) offer health benefits for the prevention of diabetes and other related health problems

Particle size

The particle size analysis on the flours extracted from the taro, yam and sweet potato revealed that the taro flour had the smallest mean diameter (2.02 µm) (Figure 1A) with a particle size distribution ranging from 1.067-64.19 µm. As opposed to the taro samples, yam and sweet potato flours and starches, contained larger particles with a distribution that resulted in two distinct peaks at 28.3 and 251 µm (Figure 1A, B). The results observed for the first peak are comparable to those previously reported (Farhat *et al*., 1999; Zaidul *et al*., 2007). Unfortunately, the appearance of the second peak has not been reported previously. The particle size of starch is one of the most important characteristics, which may influence other physicochemical properties such as swelling power; paste clarity, and water-binding capacity (Singh *et al*., 2003). With these factors in mind the use of taro starch may be applicable for several different applications within the food industry, particularly products that require starch that offers a smaller particle size allowing for smooth textured starch gel (Tattiyakul *et al*., 2005). Past studies have indicated this, such as, it was shown that the fine granules of taro starch improved binding and reduced breakage of a snack product (Huang *et al*., 2006).

Swelling power

The changes in swelling power of taro, yam, and sweet potato flours and starches are shown in Figures 2A and 2B. The granules of sweet potato flour swelled at a lower temperature (~60°C) in comparison to those of taro and yam, which swelled at ~70°C. The starch granules start to swell rapidly only after the temperature reached the onset of the gelatinisation temperature (Jacguier *et al*., 2006). The onset gelatinisation temperature (T_o) of taro, yam, or sweet potato flours (74.32, 74.21, and 62.56°C respectively; Table 4) as determined by DSC, corresponded to the start of the rapid increase of swelling power of these flours (Figure 2A). The swelling power of taro and yam flours increased steadily with a temperature rise from 70 to 90°C, as opposed to sweet potato flour with a rapid change of swelling power in this temperature region. At 90°C, the swelling power of the sweet potato flour was 3 to 4 times greater than that of taro and yam flours but with a poor integrity (Figure 2A). The swelling power of flour samples is often related to their protein and starch contents (Woolfe, 1992). A higher protein content in flour may cause the starch granules to be embedded within a stiff protein matrix, which subsequently limits the access of the starch to water and restricts the swelling power. The obtained results fit these previous observations with flours lower in protein and higher in total starch content having a higher swelling ability (Table 1; Figure 2A). In addition to protein content, a higher concentration of phosphorous may increase hydration and swelling power by weakening the extent of bonding within the crystalline domain (Singh *et al.*, 2003). Furthermore, the amylopectin is primarily responsible for granule swelling, thus higher amylose content would reduce the swelling factor of starch (Tester and Morisson, 1990). However, in the current study, there was no apparent correlation between the amylose content and swelling power of the sweet potato flour, which somewhat contradicted a negative correlation previously reported by Collado *et al.* (1999).

Paste clarity

As depicted in Figure 3A, sweet potato flour had a higher paste clarity compared to taro and yam flours during the 7-day storage. This large difference was alleviated upon starch extraction, which resulted in comparable paste clarities of sweet potato and taro starches at the end of the testing period. Paste clarity is another important property of flour or starch that governs which applications different flours or starches may have for food processing. For example transparent starch paste is required to thicken fruit pies as opposed to opaque paste, which is more suitable for salad dressing (Craig *et al.*, 1989). The results presented here indicate differences in paste clarity, which may determine which species of tuber's flour, or starch may be used for different applications in the food industry. There are many factors that may also influence paste clarity such as amylose, lipid and protein contents, (Craig *et al.*, 1989), botanical source, particle size of granules, total solids concentration, degree of granule dispersion, and the capacity of granules to form aggregates (Amani *et al.*, 2005) which have not been examined to any great extent in this study. However the results here for the sweet potato indicate that its flour and starch may offer high enough paste clarity for use in food products requiring this.

Pasting properties

The pasting behavior of the tuber's starches was studied by observing changes in the viscosity of a starch system based on the rheological principals (Huang *et al.*, 2006). Among the flour samples, taro and yam flours had the highest peak time (Table 3), which may indicate a greater structural rigidity in comparison to sweet potato flour (Leon *et al.*, 2006). This structural rigidity was also observed from the low swelling power as discussed previously. In regard to the pasting temperatures, the sweet potato flour had the highest (80.98°C) with the yam flour having the lowest (72.75°C), which could be related to the starch concentrations of the samples (Table 1) with sweet potato having the lowest TS content yet the highest pasting temperature.

Also sweet potato flour had lowest peak viscosity as opposed to the taro flour (Table 3). This observation might have been influenced by lower rigidity of starch granules in sweet potato, which in turn caused instability and consequently disruption upon the heating and stirring treatment (Leon *et al.*,

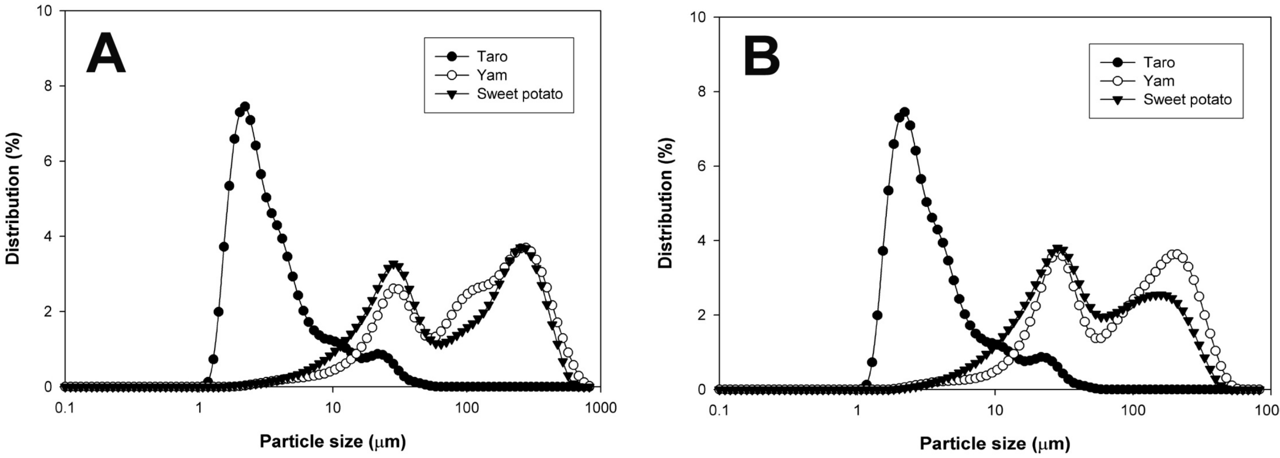

Figure 1. Particle size distribution of flours (A) and starches (B) extracted from taro, yam and sweet potato

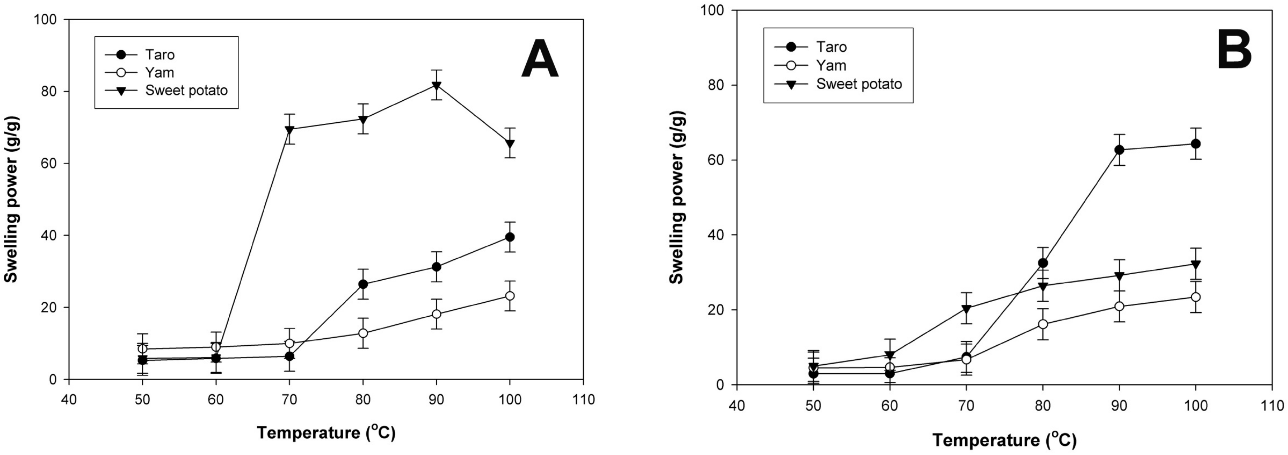

Figure 2. Swelling power of flours (A) and starches (B) extracted fr0m taro, yam and sweet potato

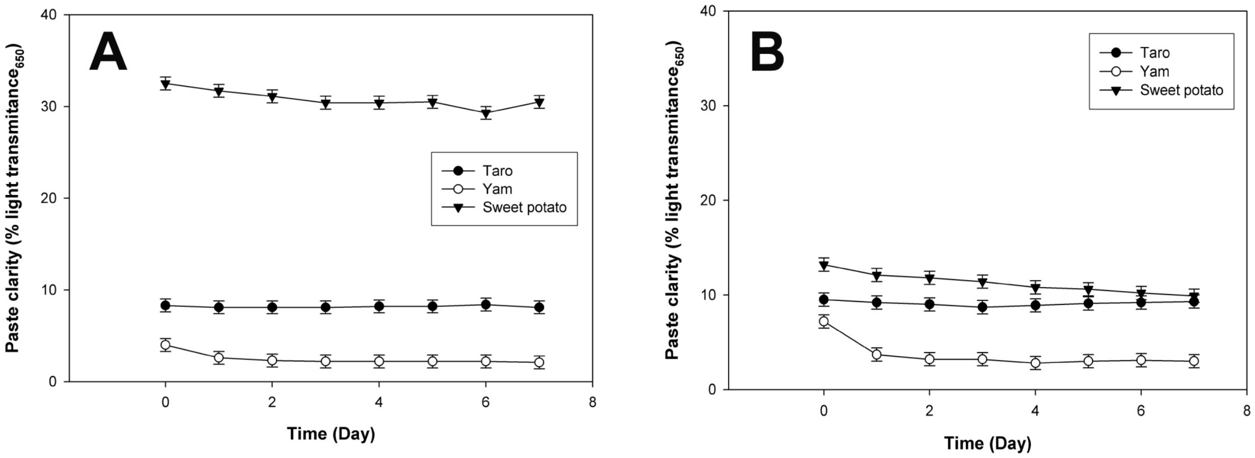

Figure 3. Paste clarity of flours (A) and starches (B) extracted from taro, yam and sweet potato

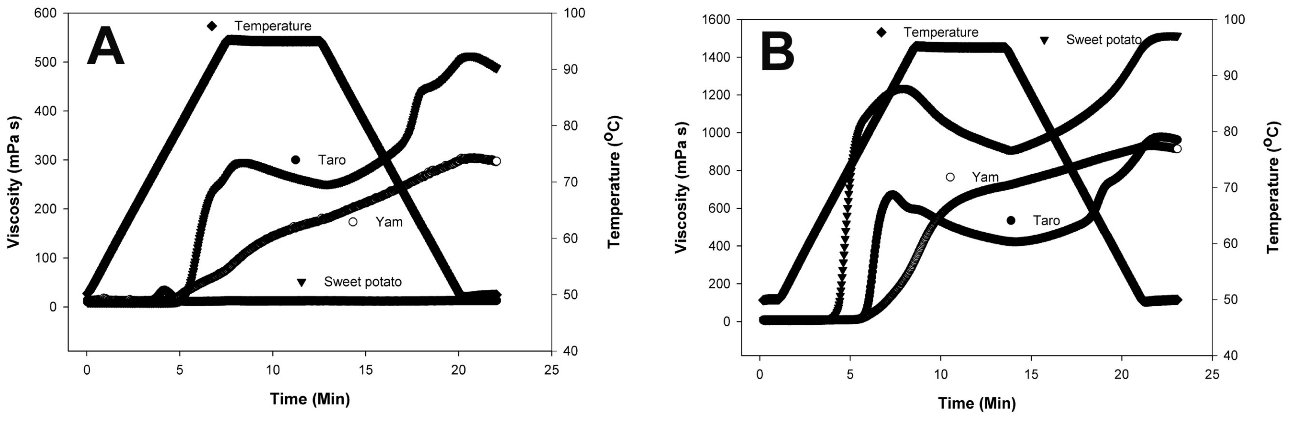

Figure 4. Pasting properties of flours (A) and starches (B) extracted from taro, yam and sweet potato flours

Table 3. Pasting characteristics of flours and starches extracted from taro, yam, and sweet potato

Pasting characteristics	Flour			Starch		
	Taro	Yam	Sweet potato	Taro	Yam	Sweet potato
Peak T^{2} (min)	8.5± 0.00^{a}	8.5±0.36^{b}	5.2±0.06^{c}	7.3± 2.66^{c}	8.5± 0.00^{a}	7.9± 1.53^{b}
Past T (^{o}C)	75.1± 0.04^{b}	72.7±2.61^{c}	80.9±0.62^{a}	72.8± 0.03^{a}	72.3± 0.03^{b}	64.4± 0.01^{c}
PV (cP)	265.8±40.06^{a}	n.a	34.5±3.86^{b}	671.5±14.25^{a}	n.a	1238.3±20.85^{c}
HS (cP)	250.6±37.19^{a}	n.a	11.1±0.65^{c}	421.9± 7.40^{b}	n.a	910.3±18.55^{a}
BD (cP)	15.2± 3.41^{b}	n.a	23.4±3.33^{a}	249.7± 7.65^{b}	n.a	328.0±36.05^{a}
SFP (cP)	221.5±25.34^{a}	n.a	-21.5±3.21^{b}	291.2± 9.97^{b}	n.a	275.7±15.98^{c}
SFT (cP)	236.8±27.67^{a}	n.a	1.8±0.19^{b}	540.9±12.75^{a}	n.a	603.7±20.30^{a}
FV (cP)	487.4±64.63^{a}	297.4±38.22^{b}	12.9±0.84^{c}	962.8±19.99^{a}	914.5±10.96^{a}	1514.0±31.75^{b}

Each mean presents an average of three independent observations; *Peak T - peak time; Past T - pasting temperature; PV - peak viscosity; HS - holding strength; BD - breakdown; SFP - setback from peak; SFT - set back from through; FV - final viscosity; n.a. – not available; Values followed by the different superscript in each row are significantly different ($P<0.05$).

2006). On the other hand, the higher peak viscosity of the taro flour compared to other flour samples could be due to the small granule size (Figure 1A), which also led to higher swelling power (Figure 2A) and subsequently higher viscosity. However, the viscosity of this flour decreased substantially afterwards, likely due to lower protein content and free leaching of amylose and amylopectin from the granules (Leon *et al*., 2006). Taro flour also showed a retrogradation tendency, indicated by the rise of viscosity during cooling period (Leon *et al*., 2006; Zaidul *et al*., 2007). Yam flour also had a tendency toward retrogradation.

However the presence of a higher protein content in the yam flour might have prolonged the starch swelling and gelatinization process leading to a steady increase of viscosity during the heating period with no apparent breakdown (Figure 4A). These results indicate that yam flour may be suitable for use in food products that require continuous thermal processing such as food for elderly and children (Rincon and Padilla, 2004).

The starch samples had similar pasting characteristics to their respective flours but with a higher viscosity, with the exception for the sweet potato starch (Figure 4A, B). These results were not unexpected since this difference could have been caused by the presence of other components in flour such as mucilage, proteins, and lipids that would interfere with the pasting process. The lower starch content in a flour sample may also lower its viscosity (Alves *et al*., 2002) as can be seen in table 1, that sweet potato had the lowest reported result for starch content. In addition to a low pasting temperature, sweet potato starch also had the highest peak viscosity most likely caused by the low protein content in this sample (Table 1). Sweet potato and taro starches also showed a substantial granular breakdown as indicated by the decrease of viscosity after peak viscosity.

Gelatinisation properties

The flour samples in this study had a higher gelatinisation temperature than the corresponding starches (Table 4). This is most likely due to the presence of other components in flour such as proteins and lipids that would obstruct the swelling of granules and thus increase the amount of heat required to reach the final swelling. Similar observations have been reported previously (Jane *et al*., 1992).

The taro flour and starch had the highest gelatinisation temperatures (T_o, T_p, and T_c), followed by yam and sweet potato (Table 4). This indicated higher stability of taro starch crystallites upon heating (Sasaki and Matsuki, 1998). The findings in this study also confirmed observations reported by Srichuwong *et al* (2005b). The perfectness of the taro starch crystallites is also reflected in its ΔH (gelatinisation enthalpy) value, which was lower than those of yam and sweet potato. ΔH is an indicator of a loss of molecular order within the granule, which increases with a decline of the degree of starch crystallinity (Tester and Morrison, 1990).

The gelatinisation temperatures of yam flour and starch were in the range from 74.21 to 84.67°C and

Table 4. Gelatinization parameters of flours and starches of taro, yam, and sweet potato

Samples	Gelatinization parameters				
	T_o (°C)*	T_p (°C)*	T_c (°C)^1	T_c - T_o (°C)^2	ΔH (J/g)^3
Flours					
Taro	74.32±2.01^a	79.75±3.72^a	87.13±3.70^a	12.81±1.69^{ab}	6.95±0.79^a
Yam	74.71±1.71^a	78.70±0.58^{ab}	84.40±0.06^a	10.20±-1.45^a	6.83±1.02^a
Sweet potato	65.9±3.80^b	73.57±1.58^a	79.36±1.48^b	13.46±0.71^b	7.41±0.54^a
Starch					
Taro	70.95±0.63^a	78.53±0.73^a	84.67±0.86^a	13.72±0.23^b	6.28±0.22^b
Yam	69.18±1.44^a	76.08±0.39^b	81.50±1.42^b	12.32±0.02^b	10.01±0.31^a
Sweet potato	56.96±0.81^b	67.97±0.09^c	75.02±0.73^c	18.05±-0.08^a	7.42±0.94^b

All means present the average of three independent replications. Values followed by the different superscript in each column are significantly different ($P<0.05$).

[1] To, Tp, and Tc indicate temperature of onset, midpoint and end of gelatinization, respectively.

[2] Tc-To indicates the gelatinisation temperature range

[3] Enthalpy of gelatinization ΔH (J/g)

69.18 to 81.5°C, respectively (Table 4). In comparison to taro and sweet potato, yam flour and starch had a narrower range of gelatinization temperature.

These results confirmed previous observations (Alves *et al*., 2002; Moorthy, 2002); however, they were slightly lower than some other reports (Farhat *et al*., 1999; Srichuwong *et al*., 2005b; Jayakody *et al*., 2007), these differences may be explained as the samples were not exactly the same.

Physicochemical properties: mucilage

Protein

Yam mucilage contained higher levels of protein (23.48%) in comparison to taro and sweet potato (13.53%) and (7.66%), respectively. However, the results obtained in this study were lower than those reported previously for yam (55.36%; Alves *et al*., 2002) and taro (20.9-40%; Jiang and Ramsden, 1999). While the difference might have been caused by a different extraction method, this could also be due to the variations of botanical origin and environmental conditions during cultivation. For example, mucilage formation is related to a plant stress response during growth and therefore related to environmental conditions (Jiang and Ramsden, 1999) as the samples were not exactly the same ones used in the reported studies and this present study, differences may be expected.

Rheological properties of mucilage

Flow behavior of mucilage solutions was assessed using controlled shear rate rheology. The data acquired during these measurements were fitted using three different rheological models, namely the Ostwald (Power law), Herschel-Buckley, and Casson. Table 5 shows the results for the main parameters in these models and corresponding R^2. In general, all three models are used to describe the flow of materials that deviate from Newtonian flow and fairly well described the flow as indicated with R^2 above 0.91. The mucilage source and its concentration had a significant ($P<0.05$) effect on all parameters of these models. The Herschel-Buckley model produced the best fit showing a clear direct relationship between concentration and pseudoplasticity; however, yield stress showed no apparent trend and was fairly similar among all tubers. The apparent differences in consistency indexes among these solutions at the same concentration, point out likely differences in composition, which needs to be further explored.

The results from this present study have demonstrated the different properties of each species of tuber examined here for their flour, starch and mucilage. These results also offer an indication of the applications in the food industry, for which each species may be suited. The results for each of the examined tubers has confirmed results found in literature, that in general, most of the tuber and root starches have higher viscosity and paste clarity in comparison to cereal starches (Craig *et al*., 1989) allowing them to be used as thickeners in certain applications such as sauces, soups, and dairy desserts. Also tuber starches gelatinize at low temperatures with a rapid and uniform swelling of granules, which is very important for noodle making (Chen *et al.*, 2003a). The results found in the present study also indicate that taro may have applications for use in several different food products due to its fine granules and small particle size and may offer improved binding and reduced breakage of products, as was shown in past studies by Huang *et al*., (2006). Taro also has a smooth-textured gel (Tattiyakul *et al*., 2005), which would make it suitable for noodle processing, which requires a smooth mouth feel and avoidance of a grainy texture (Moorthy, 2002). Furthermore taro starch may have applications in bread production as a finer particle size is required for better light reflection on the porous structure of bread giving whiter bread crumbs and better consumer perception (Kaletunc and Kenneth 1999). Also as it has a high content of resistant starch therefore the use of taro in any of the above products may offer additional health properties.

Past studies have also shown that sweet potato flour may potentially be used in noodle processing and bread production as well (Chen *et al*., 2003a), while its starch can be used as an ingredient in bread, biscuits, cake, juice and noodles (Zhang and Oates, 1999). The main application of yam flour currently is in the production of bread and snacks (Alves *et al*., 2002).

Also this rather preliminary assessment of mucilage from tubers has shown that these protein rich extracts could be used in various preparations with no noticeable effect on viscosity, as well as offering health promoting benefits such as, their angiotensin converting enzyme inhibitory (Lee *et al*., 2003) and antioxidative activities (Nagai *et al*., 2006). However these factors require further investigation.

Conclusion

As this study has shown there are a great many potential applications for tuber starch, flour and mucilage, within the food industry. Each of these components having different physiochemical or beneficial health properties, which may be further examined for either the development of entirely

Table 5. Flow behavior of taro, yam and sweet potato mucilage at various concentration fitted by Herschel-Buckley, Ostwald (Power law), and Casson models.

Source	Conc., %	Herschel Buckley				Ostwald (Power law)			Casson		
		σ (mPa)	K (mPas^n)		R^2	K (mPas^n)	n	R2	K_{0c} (mPas)$^{1/2}$	K_c (mPas)$^{1/2}$	R2
Sweet potato	10	2.53	14.68	0.68	0.96	13.55	0.54	0.97	54.20	42.35	0.95
	5	3.27	2.59	0.95	0.98	11.44	0.59	0.97	51.82	28.31	0.91
	2.5	2.82	1.02	0.99	0.98	10.38	0.64	0.96	48.94	25.47	0.93
Yam	10	1.52	45.55	0.82	0.98	17.58	0.24	0.93	38.18	155.69	0.95
	5	2.83	5.47	0.93	0.97	13.91	0.50	0.94	55.17	51.65	0.93
	2.5	2.27	2.37	0.92	0.97	12.57	0.56	0.99	50.54	34.53	0.96
Taro	10	1.29	14.28	0.57	0.93	55.70	0.53	0.99	50.55	48.90	0.92
	5	1.18	4.64	0.79	0.96	20.85	0.57	0.94	48.98	40.69	0.99
	2.5	0.79	2.69	0.86	0.94	12.57	0.73	0.92	35.49	33.03	0.96

All data reported are representing the mean of three independent replications.

new food products or for the replacement in current food products from the more traditional sources of starch and flour. The examination of the various physicochemical properties found here in this study demonstrates the potential of these products in food processing. Such results may allow for informed choices or diversity of choice when sourcing new ingredients or ingredients with properties to enhance product production and development.

Based on the results of the physicochemical properties of their main extracts (flour, starch, mucilage), taro, yam and sweet potato it can be seen that these tubers products have a good potential to be used in the food industry. The high viscosity of taro starches would make them very useful in food applications where high thickening power is desired as well as the small particle size being useful for noodle or bread production. The stability of yam flour and starch against heat and mechanical treatment would also be useful in many food applications. The low viscosity of sweet potato flour is desirable in the food industry for applications that require lower viscosity and the high paste clarity would make it useful for products where this is required as a thickening agent In addition to the useful individual properties of these tubers, the high amount of resistant starch and the slow digestibility make the use of these tubers and roots valuable alternative carbohydrate sources, in terms of also offering health benefits such as, aiding in the prevention of certain diseases such as obesity and hypertension. Added to this, the absence of gluten in these tubers would be advantageous for producing foods for people suffering from celiac disease and may also aid in its prevention. Therefore these tubers may be seen as having very broad applications within the food industry.

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References

Achille, T.F., Georges, A.N. and Alphonse, K. 2007. Contribution to light transmittance modelling in starch media. African Journal of Biotechnology 6: 569-575.

Alves, R.M., Grossmann, M.V., Ferrero, C., Zaritzky, N.E., Martino, M.N. and Sierakoski, M.R. 2002. Chemical and functional characterization of products obtained from yam tubers. Starch 54: 476-481.

Amani, N.G.G., Kamenan, A., Sabate, A.R. and Colonna, P. 2005. Stability of yam starch gels during processing, African Journal of Biotechnology 4: 94-101.

American Association of Cereal Chemists. 2000. Approved methods of the AACC. 10th ed. St.Paul, MN.

Chen, Z., Schols, H.A. and Voragen, A.G.J. 2003a. Starch granule size strongly determines starch noodle processing and noodle quality. Journal of Food Science 68: 1584-1589.

Chen, Z., Schols, H.A. and Voragen, A.G.J. 2003b. Physicochemical properties of starches obtained from three different varieties of Chinese sweet potatoes. Journal of Food Science 68: 431-437.

Collado, L.S., Mabesa, R.C. and Corke, H. 1999. Genetic variation in the physical properties of sweet potato starch. Journal of Agriculture and Food Chemistry 47: 4195-4201.

Craig, S.A.S., Maningat, C.C., Seib, P.A. and Hoseney, R.C. 1989. Starch paste clarity. Cereal Chemistry 66: 173-182.

Farhat, I.A., Oguntona, T. and Neale, R.J. 1999. Characterization of starches from West African yams. Journal of the Science of Food and Agriculture 79: 2105-2112.

Freitas, R.A., Paula, R.C., Feitosa, J.P.A., Rocha, S. and Sierakowski, M.R. 2004. Amylose contents, rheological properties and gelatinisation kinetics of yam (*Dioscorea alata*) and cassava (*Manihot utilisima*) starches. Carbohydrate Polymers 55: 3-8.

Gebre-Mariam, T. and Schimdt, P.C. 1998. Some physicochemical properties of *Dioscorea alata* from Ethiopia. Starch 50: 241-246.

Hoover, R. and Ratnayake, W. S. 2005. Determination of total amylose content of starch. In: Handbook of Food Analytical Chemistry: Water, Proteins, Enzymes, Lipids, and Carbohydrates (R. E. Wrolstad, T. E. Acree, E. A. Decker et al, Eds). Pp. 689-693. John Wiley and Sons.

Hoover, R. and Sosulski, F. 1985. Studies on the functional characteristics and digestibility of starches from Phaseolus vulgaris biotypes. Starch 37: 181-191.

Huang, C.C., Lin, M.C. and Wang, C.C.R. 2006. Changes in morphological, thermal, and pasting properties of yam (*Dioscorea alata*) starch during growth. Carbohydrate Polymers 64: 524-531.

Hung, P.V. and Morita, N. 2005. Physicochemical properties and enzymatic digestibility of starch from edible canna (*Canna edulis*) grown in Vietnam. Carbohydrate Polymers 61: 314-321.

Jacguier, J.C., Kaar, A., Lyng, J.G., Morgan, D.J. and McKenna, B.M. 2006. Influence of granule size on the flow behaviour of heated rice starch dispersions in excess water. Carbohydrate Polymers 66: 425-434.

Jane, J., Wong, K.S. and McPherson, A.E. 1997. Branch-structure difference in starches of A- and B- type X-ray patterns revealed by their Naegali dextrins. Carbohydrate Research 300: 219-227.

Jane, J.L., Shen, L., Lim, S., Kasemsuwan, T. and Nip, W.K. 1992. Physical and chemical studies of taro starches and flours. Cereal Chemistry 69: 528-535.

Jayakody, L., Hoover, R., Liu, Q. and Donner, E. 2007. Studies on tuber starches. II. Molecular structure, composition and physicochemical properties of yam (*Dioscorea sp*) starches grown in Sri Lanka. Carbohydrate Polymers 69: 148-163.

Jiang, G. and Ramsden, L. 1999. Characterisation and yield of the arabinogalactan-protein mucilage of taro corms. Journal of the Science of Food and Agriculture 79: 671-674

Lee, M.H., Lin, Y.S., Lin, Y.H., Hsu, F.L. and Hou, W.C. 2003. The mucilage of yam (*Dioscorea batatas* Decne) tuber exhibited angiotensin converting enzyme inhibitory activities. Botanical Bulletin of Academia Sinica 44: 267-273.

Leon, A.E., Barrera, G.N., Perez, G.T., Ribotta, P.D. and Rosell, C.M. 2006. Effect of damaged starch levels on flour-thermal behaviour and bread staling. European Food Research and Technology 224: 187-192.

Liu, Q., Donner, E., Yin, Y., Huang, R.L. and Fan, M.Z. 2006. The physicochemical properties and in vitro digestibility of selected cereals, tubers, and legumes grown in China. Food Chemistry 99: 470-477.

Mali, S., Ferrero, C., Redigonda, V., Beleia, A.P., Grossmann, M.V. and Zaritzky, N.E. 2003. Influence of pH and hydrocolloids addition on yam (Dioscorea alata) starch pastes stability. Food Science and Technology 36: 475-481.

Medina-Torres, L. Fuente, E.B.L, Sanchez, B.T., and Katthain, R. 2000. Rheological properties of the mucilage gum (*Opuntia ficus indica*). Food Hydrocolloids 14: 417–424.

Moorthy, S.N. 2002. Physicochemical and functional properties of tropical tuber starches: A review. Starch 54: 559-592.

Nagai, T., Suzuki, N. and Nagashima, T. 2006. Antioxidative activity of water extracts from the yam (*Dioscorea opposita* Thunb.) tuber mucilage *tororo.* European Journal Lipid Science and Technology 108: 526-531.

Noda, T., Kimura, T., Otani, M., Ideta, O., Shimada, T., Saito, A. and Suda, I. (2002). Physicochemical properties of amylose-free starch from transgenic sweet potato. Carbohydrate Polymers 49: 253-260.

Onwulata, C.I. and Konstance, R.P. 2002. Viscous properties of taro flour extruded with whey proteins to stimulate weaning foods. Journal of Food Processing and Preservation 26: 179-194.

Ratnayake, W.S., Hoover, R., Shahidi, F., Parera, C. and Jane, J. 2001. Composition, molecular structure, and physicochemical properties of starches from four field pea (*Pisum sativum* L.) cultivars. Food Chemistry 74: 189-202.

Rekha, M.R. and Padmaja, G. 2002. Alpha-amylase inhibitor changes during processing of sweet potato and taro tubers. Plant Food for Human Nutrition 52: 285-294.

Rincon, A.M. and Padilla, F.C. 2004. Physicochemical properties of breadfruit (*Artocarpus altilis*) starch from Margarita island, Venezuela. Archivos Latinoamericanos de Nutricion.

Santacruz, S., Rualesa, J. and. Eliasson, A.C. 2003. Three under-utilised sources of starch from the Andean region in Ecuador. Part II. Rheological characterization. Carbohydrate Polymers 51: 85-92.

Sasaki, T. and Matsuki, J. 1998. Effect of wheat starch structure on swelling power. Cereal Chemistry 75: 525-529.

Singh, N., Singh, J., Kaur, L., Sodhi, N.S. and Gill, B.S. 2003. Morphological, thermal and rheological properties of starches from different botanical sources. Food Chemistry 81: 219-231.

Snow, P., and O'Dea, K. 1981. Factors affecting the rate of hydrolysis of starch in food. American Journal Clinical Nutrition 34: 2721-2727.

Srichuwong, S., Sunarti, T.C., Mishima, T., Isono, N. and Hisamatsu, M. 2005a. Starches from different botanical sources II: Contribution of amylopectin fine structure to thermal properties and enzyme digestibility. Carbohydrate Polymers 60: 529-538.

Srichuwong, S., Sunarti, T.C., Mishima, T., Isono, N. and Hisamatsu, M. 2005b. Starches from different botanical sources II: Contribution of starch structure to swelling and pasting properties. Carbohydrate Polymers 62: 25-34.

Swinkels, J.J.M. 1985. Composition and properties of commercial native starches. Starch, 37: 1-5.

Tattiyakul, J., Asavasaksakul, S. and Pradipasena, P. (2006). Chemical and physical properties of flour extracted from taro *Colocasia esculenta* (L.) Schott grown in different regions in Thailand. Science Asia 32: 279-284.

Tester, R.F. and Morrison, W.R. 1990. Swelling and gelatinisation of cereal starches. I. Effect of amylopectin, amylose and lipids. Cereal Chemistry 67: 551-559.

Woolfe, J.A. 1992. Sweet potato: an untapped food resource. Pp. 1-5. Cambridge: Cambridge University Press.

Zaidul, I.S.M., Norulaini, N.A.N., Omar, A.K.M., Yamauchi, H. and Noda, T. 2007. RVA analysis of mixtures of wheat flour and potato, sweet potato, yam, and cassava starches. Carbohydrate Polymers 69: 784-791.

Zhang, T. and Oates, C.G. 1999. Relationship between α-amylose degradation and physico-chemical properties of sweet potato starches. Food Chemistry 65: 157-163.