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A Comparative Study on the Resistant Starch Content from Different Botanical Sources in Relation to their Physicochemical Properties

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Abstract

Resistant starch (RS), a functional food ingredient and a type of fibre that provides the benefits of both insoluble and soluble fibres, gains attention due to its unique functional and health attributes. The aim of this study was to investigate the resistant starch content in the starch isolated from different botanical sources such as cereals (maize, rice, oats, wheat, barley), legumes (lentil, mung bean), vegetable (raw banana), and roots/tubers (potato, cassava, sweet potato and arrowroot). The rapidly digestible starch (RDS), slowly digestible starch (SDS) and RS contents in the starch samples were determined and related with their physiochemical and functional properties. The study showed that the starch from different sources varied significantly in their chemical, physical and functional properties as well as in RS content. The highest RS content was observed in lentil starch (5.3%) and lowest in oats starch (1.3%). In general, RS content was lower for starch extracted from roots and tubers compared to that of cereals and legumes. The RDS content of maize starch was the highest (95.2%) and that of barley starch was the lowest (69.5%), whereas the SDS showed a reverse trend. The RDS and RS contents showed a positive correlation with amylose content in the starch. The highest amylose content was possessed by lentil starch (28.5%) which also showed the highest RS content among all the selected starch sources.

Key words: Resistant starch, RDS, SDS, legumes, cereals, root & tubers

Introduction

Novel food culture and related metabolic syndromes are vexing problems faced by large population worldwide due to improper choice of food. The amazing trend of excess food consumption seems to be highly relevant in this health oriented era. Improper diet and bad eating habits subsequently leads to disorders in energy utilization and storage, which show the clear path to obesity, cardiovascular diseases and diabetes which can be described as new generation diseases (Ludwig, 2002). The consumption of food which contains high calorific value leads to such problems. For a measurable control of metabolic syndromes, proper choice of food is necessary which offers better satiety, decreased postprandial blood glucose level and this can be achieved to a certain extent by Resistant Starch (RS), which breaks the long lasting concept of highly digestible nature of starch (Cummings and Englyst, 1991). RS, an undigested portion of starch which gives low calories, surpasses digestion in small intestine and provides energy and nutrition for the colonial micro flora in large intestine (Champ et al., 1999). RS is the final product of a sequence of enzymatic degradation. It is described as a fibre with peculiar bland flavour, white color and low water holding capacity.

There are five different types of RS based on the degree of digestibility and sources from which they are produced (Lunn and Buttriss, 2007; Jane and Robyt, 1984). RS1 and RS2 are the major components of un-processed food

stuff, whereas RS3 is formed after cooking process like cooking and cooling. RS1 type starch is entrapped and protected from digestive enzymes by a matrix of the starch sources which mainly include partly milled seeds and legumes (Englyst and Cummings, 1992). Food sources like green banana and raw potato which have ungelatinized native granules with type B crystallinity are included in RS2. Food processing like cooking and cooling make starch non-granular and crystalline and they become resistant to digestive enzymes. This type of starch comes under the category RS3. RS4 resists digestion due to newly formed chemical bonds (Wang et al., 2002). RS5 is amylose-lipid complex which restricts granule swelling, possesses high dissociation temperature and is resistant to amylase hydrolysis (Jane and Robyt, 1984). Due to pre-processing of foods, RS1 and RS2 slowly, but completely get digested, whereas RS3 resists digestion.

The factors which make resistant starch unique from other carbohydrates are its positive health benefits as a dietary fibre. The fermentation of RS boosts up the production of butyrate in comparison with other fermentable carbohydrates which are highly important for the epithelial tissue in the colon (Englyst and Macfarlane, 1986). As RS is not absorbed, it will cause minimal increase of postprandial glucose and insulin responses which give a new remedial measure for diabetic patients. As RS is associated with low calorie, less fat storage happens and at the same time enhances absorption of calcium, magnesium and other minerals. Compared with the mediocre starch and flour sources, naturally occurring RS (particularly RS2) has lower impact on blood glucose and insulin which are important for managing metabolic syndromes. Due to the reported health benefits a popular press gave publicity to RS as "weight loss wonder food" by giving a 'super food' status to it (Nikoley, 2014).

The starch with high RDS content increases blood glucose level rapidly and data on various starch fractions in different botanical origin will help the patients suffering from metabolic syndrome like diabetes to restrict the usage of such starch sources. In the present study, an attempt has been made to investigate the resistant starch content and digestibility pattern of starches isolated from fifteen different botanical origins which include cereals, legumes, tubers and vegetables as well as to study the various physiochemical and functional properties of each starch.

Materials and Methods

The starch sources selected for the study included various cereals, legumes, raw banana and tuber crops, which included both temperate (potato) and tropical tuber crops (cassava, sweet potato and arrowroot). Rice-raw and parboiled (*Oryza sativa*), maize (*Zea mays*), oats (*Avena sativa*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), lentil (*Lens culinaris*), mung bean (*Vigna radiata*), potato (*Solanum tuberosum*) and banana (*Musa acuminate*, cultivar-Nendran) were commercial samples purchased from the local market. The tuber crops viz., cassava (*Manihot esculenta* Crantz; variety M4 and Sree Jaya, a short duration variety), sweet potato (*Ipomoea batatas)*; Variety Sree Arun (cream flesh) and Sree Kanaka (yellow flesh) and arrowroot (*Maranta arundinacea*) were obtained from ICAR-Central Tuber Crops Research Institute farm. The enzymes used for the study included amyloglucosidase from *Aspergillus niger* (Cat.No.A9913, Sigma-Aldrich, USA), pepsin (EC 3.4.23.1; M/s Sigma-Aldrich, USA), Panzynorm tablet (M/s German Remedies India Ltd., Mumbai, India), porcine pancreatic amylase (Cat. No.P7545, Sigma-Aldrich) and GOD (EC 1.1.3.4)-PAP (M/s Beacon Diagnostics Pvt. Ltd., Gujarat, India).

Isolation of starch

Standard methods were used for the extraction of starch from different sources. Dried grains of cereals as well as legume seeds were steeped in water before starch extraction. In the case of lentil and mung bean, the method adopted by Singh et al. (1989) was used, where lentil was steeped in a solution containing 0.16% of sodium hydrogen sulfite. It was then ground and screened through 100 mesh sieve. The settled starch was re-suspended in water, washed and sundried. In the case of banana, the extraction method of Waliszewskia et al. (2003) was adopted. For rice, barley, corn and oats, alkali steeping was done to remove the proteins (Wang and Wang, 2001). Batter process of starch isolation was employed for wheat which included the removal of gluten. Potato starch was extracted by the method adopted by Singh and Singh (2001). Starch from other tuber sources were extracted after cleaning the tubers. Then the tubers were peeled, sliced and ground. The resultant slurry was then sieved and filtered with excess water and the starch milk was kept overnight. The sedimented starch cake was washed with water, allowed to settle the starch, decanted, sundried and powdered.

FTIR analysis

The FTIR spectra of starch samples were taken on a Perkin Elmer FTIR instrument (Spectrum RX1) using a diffused reflectance accessory (DRA). The background spectrum was that of potassium bromide.

Determination of starch composition

The nitrogen content in the sample was estimated by micro Kjeldhal method and the crude protein content was determined according to AOAC Official method (1960). The total starch content in the samples was determined by a titrimetric method using alkaline potassium ferricyanide (Moorthy and Padmaja, 2002). The moisture, ash and crude fibre contents were determined by AOAC Official methods (1999 and 1975). Fat was extracted with alcohol-ether mixture as well as chloroform-methanol mixture and quantified (Floch et al., 1957). The total amylose content in different starch samples was estimated using the standard procedure (Sowbhagya and Bhattacharya, 1971; Shanty et al., 1980). In short starch (100 mg) was weighed in a standard flask. Ethanol (1 ml) and NaOH (10 ml, 1N) were added and kept overnight. The solution was then made up to 100 ml and 2 ml aliquot was taken and neutralized. The color was developed by KI-I_2 solution and absorbance was measured at 620 nm.

Digestibility properties

RDS, SDS and RS contents

The RDS, SDS and RS contents in the starch samples were determined according to the procedure modified from the original methods of Englyst et al. (1986), McCleary and Monaghan (2002) and Kim et al. (2008). Starch was gelatinized in HCl-KCl buffer (pH = 1.5) and incubated with pepsin for 1hour. It was then incubated for 10 minutes with phosphate buffer (pH = 6.9) followed by Panzynorm tablet which contain lipase, amylase and protease for 20 minutes. One ml of the supernatant was withdrawn and treated with sodium acetate buffer (pH = 4.8) for half an hour at 60 ºC, followed by treatment with amyloglucosidase. The glucose formed was measured using GOD-PAP (glucose oxidase and phenol and 4-aminophenazone) method. The same procedure was repeated at 20 minutes time interval up to 120 minutes. The rapidly digested starch (RDS) was the total starch digested within 20 minutes and slowly digestible starch (SDS) was that digested between 20 and 120 minutes. The RS content was calculated as follows:

RS (%) = [Total starch - (RDS + SDS)] X 100

In vitro starch digestibility

The starch (100 mg) was weighed out into a 100 ml conical flask, sodium phosphate buffer (10 ml, pH 6.9) was added and gelatinized by keeping the flask in a boiling water bath for 20 minutes. After cooling the flasks, porcine pancreatic amylase (digestibility unit of 500,000) was added (0.5 ml, 25 mg enzyme in 25 ml phosphate buffer) and incubated for 60 minutes. The reducing sugar formed after 30 minutes and 60 minutes of enzyme incubation was determined by Nelson's method (1944). The *in vitro* digestibility was calculated as percentage.

Physicochemical properties

Water binding capacity

Water binding capacity (WBC) was determined by the method given by Yamazaki (1953). The starch suspension in distilled water was stirred using a mechanical stirrer for 1 hour at room temperature and then centrifuged. The water was decanted and wet starch was then weighed. WBC was calculated as follows:

WBC = Weight of wet starch (g)/Weight of starch taken (g)

Viscosity

The hot paste and cold paste viscosities of the starch paste (4 % w/v) were determined at 90°C and 30°C respectively, using a Brookfield viscometer.

Differential scanning calorimetry (DSC)

The starch samples were weighed in to aluminium DSC pans, and deionized water was added to the starch in the ratio of 1:2. The pans were sealed hermetically and allowed to equilibrate at room temperature for about 2 hours before testing. Thermal scans were performed from 25 to 100 ºC at a heating rate of 10 ºC min^{-1} using an empty pan as reference. The onset (T_o), peak (T_p) and end (T_e) gelatinization temperatures were determined from the DSC curves using a built-in software. Enthalpy change of gelatinization (ΔH) was determined based on the area of the endothermic peak.

Statistical analysis

The data reported were the average of triplicate observations and were analyzed by single factor analysis of variance (ANOVA) using SAS 9.3. Comparison of

means was made using Duncan's Multiple Range Test (DMRT). The level of significance was set at $P < 0.05$.

Results and Discussion

Composition of starch

The chemical analysis of starch which includes moisture, lipid, protein, total starch, ash and amylose content in different starches are presented in Table1. The moisture content was less than 15 per cent for all the starches. The lipid content was highest in the starch from oats ($1.8 \pm 0.07\%$), followed by barley ($1.5 \pm 0.11\%$), whereas it was significantly lower in tuber and rice starches. Earlier Hoover (2001) reported that the total lipid in roots starches was in the range of 0.1-1.14% and the results are in agreement with earlier reports. The crude protein content was higher in almost all cereal and legume starches with a highest value of 1.9 % possessed by barley, banana and par-boiled rice starches; whereas, it was significantly lower in all tuber starches (Table 1). The total starch content was highest for arrowroot starch ($89.6 \pm 1.63\%$) followed by starch from banana and the cream fleshed sweet potato variety. The lowest starch content was shown by oats ($82.5 \pm 1.01\%$). The comparatively higher starch content and more purity in the case of tuber starches could be due to the lesser amount of extraneous compounds present in them. The ash content was in the range of $0.6 \pm 0.01\%$ to $0.08 \pm 0.01\%$. All starches contained less quantity of lipids, ash and protein. From the correlation analysis, it was found that there was a significant ($P < 0.05$) negative correlation of starch content with lipid and protein contents, which implies more purity of starch if lipids and proteins are less. The botanical origin of the plant and soil type during plant growth stage could be the reasons for the difference in lipid and ash content in case of cereals and legumes (Morrison and Azudin, 1987).

The amylose content in starch varied significantly among the different botanical sources (Table 1). It was comparatively higher for legume starches with a highest value of $28.5 \pm 0.09\%$ for lentil starch followed by potato starch (24.3 ± 0.15). Among cereals, maize and wheat possessed higher amylose content, whereas, barley starch has the lowest amylose. This is in agreement with the reports of Nuwamanya et al. (2011). In the tropical tuber

Table 1. Proximate composition of starch isolated from different botanical sources

Starch source	Moisture	Lipid	Protein	Starch	Ash	Amylose content
	(% on dry weight basis)					
Barley	9.7 ± 0.20^{e}	1.5 ± 0.11^{b}	1.93 ± 0.0^{a}	84.9 ± 0.46^{def}	0.43 ± 0.0^{d}	17.6 ± 0.30^{hi}
Oats	10.1 ± 0.02^{e}	1.8 ± 0.07^{a}	1.75 ± 0.0^{c}	82.5 ± 1.01^{ef}	0.48 ± 0.0^{c}	18.4 ± 0.09^{fghi}
Wheat	8.5 ± 0.25^{f}	0.8 ± 0.03^{c}	1.77 ± 0.0^{bc}	84.3 ± 1.92^{f}	0.60 ± 0.01^{a}	21.1 ± 0.13^{cd}
Par-boiled rice	8.4 ± 0.0^{f}	0.05 ± 0.0^{j}	1.92 ± 0.0^{a}	88.6 ± 1.95^{bcd}	0.23 ± 0.03^{h}	19.3 ± 0.23^{fg}
Raw rice	10.0 ± 0.07^{e}	0.2 ± 0.0^{i}	1.2 ± 0.25^{d}	87.3 ± 2.31^{ab}	0.20 ± 0.01^{i}	19.2 ± 0.04^{fe}
Maize	11.6 ± 0.06^{a}	0.58 ± 0.03^{d}	0.84 ± 0.04^{f}	87.3 ± 1.14^{abcd}	0.51 ± 0.0^{b}	20.3 ± 0.09^{de}
Lentil	13.9 ± 0.07^{a}	0.78 ± 0.04^{c}	1.05 ± 0.00^{e}	86.3 ± 0.43^{bcd}	0.13 ± 0.01^{j}	28.5 ± 0.09^{a}
Mung bean	8.8 ± 0.05^{f}	0.1 ± 0.0^{j}	1.05 ± 0.05^{de}	85.9 ± 3.27^{dc}	0.19 ± 0.02^{i}	28.4 ± 1.03^{a}
Banana	11.1 ± 0.06^{c}	0.33 ± 0.03^{gh}	1.9 ± 0.01^{ab}	88.9 ± 2.32^{abcd}	0.32 ± 0.01^{g}	17.3 ± 0.23^{hi}
Cassava (M4)	11.8 ± 0.09^{a}	0.25 ± 0.0^{ih}	0.52 ± 0.0^{g}	86.5 ± 0.04^{bcd}	0.21 ± 0.00^{i}	21.7 ± 0.59^{c}
Cassava (Sree Jaya-short duration)	11.5 ± 0.20^{a}	0.20 ± 0.0^{i}	0.61 ± 0.0^{g}	86.7 ± 0.57^{abcd}	0.23 ± 0.01^{h}	18.7 ± 0.05^{fghi}
Sweet potato (Sree Arun)	7.8 ± 0.41^{g}	0.45 ± 0.0^{ef}	0.17 ± 0.0^{h}	88.9 ± 0.96^{abc}	0.35 ± 0.0^{e}	19.7 ± 0.88^{fgh}
Sweet potato (Sree Kanaka-carotene rich variety)	11.6 ± 0.01^{a}	0.25 ± 0.0^{ih}	0.67 ± 0.0^{g}	87.9 ± 0.45^{abcd}	0.32 ± 0.01^{g}	17.1 ± 1.09^{i}
Arrowroot	10.6 ± 0.07^{d}	0.4 ± 0.0^{gf}	0.61 ± 0.0^{g}	89.6 ± 1.63^{a}	0.08 ± 0.01^{k}	17.9 ± 0.62^{ghi}
Potato	13.7 ± 0.51^{a}	0.53 ± 0.03^{de}	0.61 ± 0.02^{g}	85.3 ± 0.08^{de}	0.33 ± 0.01^{f}	24.3 ± 0.15^{b}

[1]Values presented are the mean of three replications

[2]Mean values in each column with different letters in the superscript are significantly different

starches, amylose ranged from 17.7 to 21.7 per cent. The amylose contents in sweet potato starch and corn starch were in good agreement with the previous report of Hung and Morita (2005) and Seetaraman et al. (2001), respectively. Zhang et al. (2005) reported that amylose content in banana starch is relatively low (10-20%). Amylose content of potato starch varies from 23 to 31 per cent (Kim et al., 1995) and that in cassava starch from 18.6 to 25.6 per cent (Hoover et al., 2001), corn starch from16.9-21.3% (Sandhu and Singh, 2007), mung bean starch from 28-34 per cent. (Kaur et al., 2011) which are in accordance with our results. Yano et al. (1985) reported that amylose content varied with the changes in climate and soil in different botanical sources. Nuwamanya et al. (2011) reported that ash, fat and protein content of cereal starches are higher compared to tuber starches, and because of this tuber and root starches show high purity and ease of extraction than cereal starches. This is in agreement with the results of present study also.

FTIR analysis

The FTIR spectra of the starch samples are presented in Figure 1. The spectra were similar for all the starches with characteristic absorption peaks of starch. The broad peak observed at 3000-3600 cm^{-1} corresponds to the absorption of hydrogen bonded O-H groups in starch, whereas the absorption at 2800-3000 cm^{-1} corresponds to –CH stretching. The skeletal mode of vibration of glycosidic linkage was observed at 900-950 cm^{-1}.

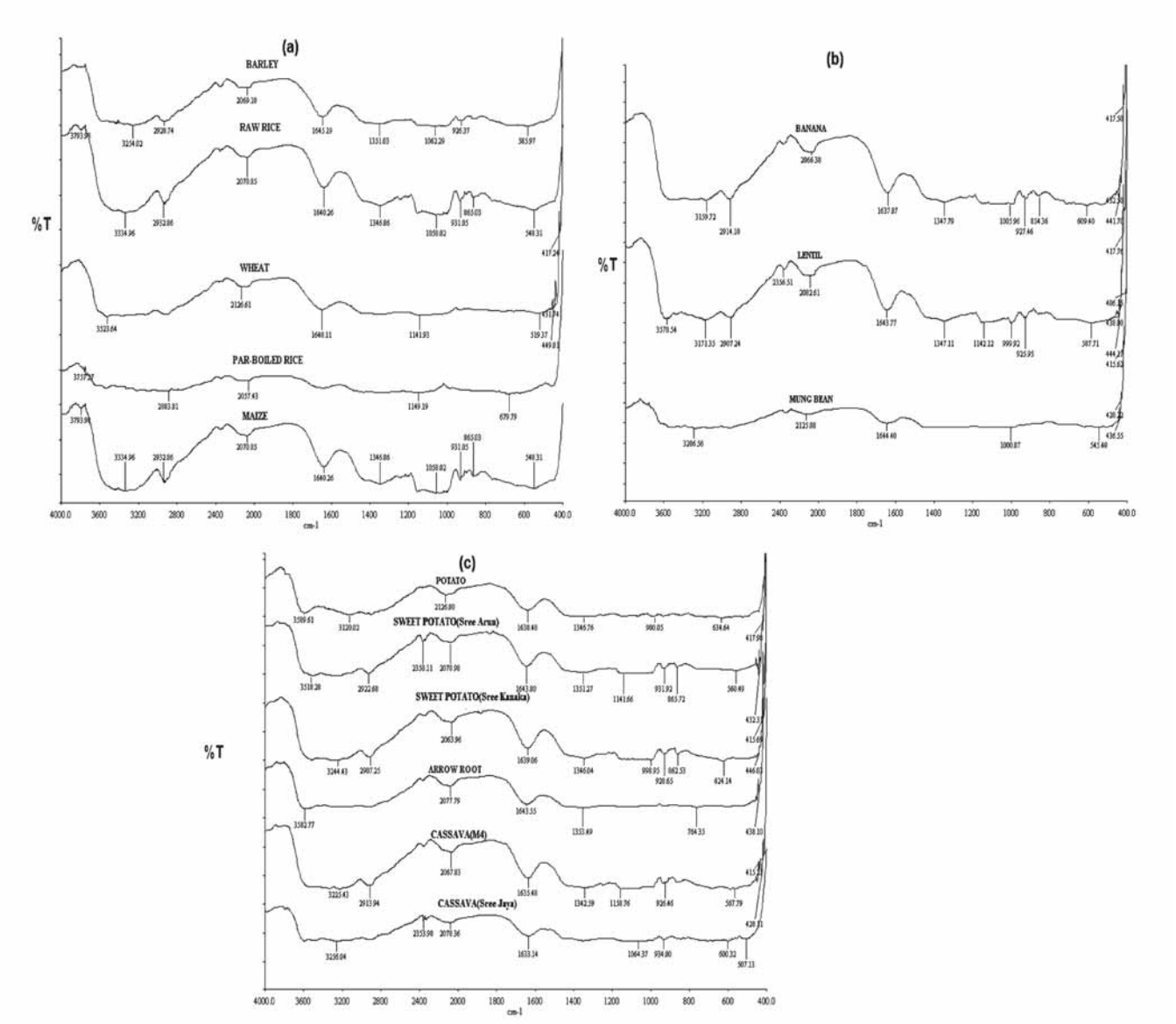

Fig. 1. FTIR spectra of (A) cereal starches, (B) legumes and banana starches and (C) tuber starches

Viscosity

The hot paste (90 °C) and cold paste (30 °C) viscosity of the starch samples measured using a Brookfield viscometer at 120 rpm is presented in Table 2. The viscosity was significantly higher for tuber starches compared to cereal and lentil starches. The highest hot paste viscosity of 50.4 cP was shown by potato starch followed by 40.1 cP for arrowroot starch and it was lowest for oats starch (2.2 cP). Among the cereals, maize starch showed comparatively higher hot paste viscosity (17.23 ± 0.4 cP), and in the case of pulses, mung bean starch showed significantly higher viscosity (26.61 ± 0.2 cP) than lentil starch (3.20 ± 0.1 cP). The cold paste viscosity was also higher for tuber starches and lowest for cereal starches. Lentil starch also showed lower cold paste viscosity. Lipid and protein contents are found to have a significant ($P < 0.05$) negative correlation to both hot and cold paste viscosities. Li et al. (2014) reported that the viscosity of tuber and root starches were significantly higher than those of cereal and legume starches, which is in agreement with the results of the present study also.

Table 2. Brookfield viscosity (4% w/v, 120 rpm) of different starch samples

Starch sample	Hot paste viscosity (90 °C)	Cold paste viscosity (30 °C)
	(cP)	
Barley	4.1 ± 0.30 [l]	5.1 ± 0.30 [m]
Oats	2.2 ± 0.60 [n]	4.4 ± 0.40 [m]
Wheat	5.2 ± 0.20 [k]	6.1 ± 0.20 [k]
Par-boiled rice	4.9 ± 0.40 [kl]	5.2 ± 0.40 [lm]
Raw rice	9.6 ± 0.30 [j]	12.3 ± 0.30 [j]
Maize	17.2 ± 0.40 [g]	19.1 ± 0.40 [g]
Lentil	3.2 ± 0.10 [m]	5.5 ± 0.15 [lk]
Mung bean	26.6 ± 0.25 [f]	31.3 ± 0.20 [f]
Banana	11.2 ± 0.40 [i]	14.4 ± 0.10 [i]
Cassava (M4)	31.0 ± 0.30 [e]	34.6 ± 0.10 [e]
Cassava (Sree Jaya-short duration)	38.5 ± 0.20 [c]	53.2 ± 0.20 [b]
Sweet potato (Sree Arun)	33.2 ± 0.30 [d]	35.5 ± 0.20 [d]
Sweet potato (Sree Kanaka-carotene rich variety)	13.1 ± 0.20 [h]	16.6 ± 0.30 [h]
Arrowroot	40.2 ± 0.30 [b]	47.2 ± 0.30 [c]
Potato	50.4 ± 0.10 [a]	60.5 ± 0.10 [a]

[1]Values presented are the mean of three replications
[2]Mean values in each column with different letters in the superscript are significantly different

Gelatinization properties

The gelatinization parameters of the starch samples are given in Table 3 and the DSC patterns are presented in Figure 2. The onset, peak and end gelatinization temperature showed significant variation among the starches. In general, gelatinization temperature was lower for cereal starches compared to tuber starches. The arrowroot starch showed highest gelatinization temperatures with a T_p of 78.2 ± 0.64 ºC. Maize and raw rice starches showed higher gelatinization temperature than other cereal starches. Raw rice starch showed a sharp peak with comparatively higher enthalpy of gelatinization also. Among the pulses, lentil starch showed a significantly lower T_o, T_p and T_e. The enthalpy of gelatinization ranged from 0.6 Jg^{-1} to 24.5 Jg^{-1}. The gelatinization temperature of corn, mung bean and potato are in consistent with the previous reports of Kaur et al. (2011), Li and Yeh (2001) and Sandhu and Singh (2007). Emmambux and Taylor (2013) reported that in African varieties, legume starches have higher gelatinization temperature than cereal starches and this result is comparable with the gelatinization parameters of lentil starch and almost all cereal starches in the present study also. From the correlation analysis, it was found that all the gelatinization parameters are negatively correlated to lipid as well as protein contents. Factors like age of the parent plant, climatic conditions and genetic origin greatly influence the gelatinization temperature of the starch source (Hung and Morita, 2005; Moorthy et al., 2002).

Water binding capacity (WBC)

The water binding capacity of the starches varied from 64.5 % to 87.2 % for different starches (Table 4). However, it was not significantly different for different starches except maize starch, which showed a WBC of 64.5%. Zuluaga et al. (2007) reported that WBC was higher for cereal starches compared to tuber starches which were almost agreeing with this study also. Variation in WBC among different starches was due to the different availability of water binding sites among starches (Wotton and Bamunuarachchi, 1978).

Table 3. DSC gelatinization parameters of different starch samples

Sample	T_o (°C)	T_p (°C)	T_e (°C)	$\Delta H(Jg^{-1})$ (°C)
Barley	58.4 ± 0.46[i]	62.5 ± 0.74[k]	68.2 ± 0.00[k]	-8.4 ± 0.96[g]
Oats	59.3 ± 0.21[g]	63.4 ± 0.11[k]	68.1 ± 0.21[j]	-0.6 ± 0.36[i]
Wheat	57.5 ± 0.86[j]	62.7 ± 0.05[k]	68.2 ± 0.63[k]	-5.1 ± 0.86[j]
Par-boiled rice	56.0 ± 0.10[k]	62.9 ± 0.12[j]	68.9 ± 0.0[k]	-0.9 ± 0.32[i]
Raw rice	70.4 ± 0.36[c]	74.3 ± 0.32[e]	79.3 ± 0.0[c]	-18.3 ± 0.25[b]
Maize	68.9 ± 0.23[e]	73.0 ± 0.05[g]	77.6 ± 0.014[e]	-11.4 ± 0.23[e]
Lentil	58.7 ± 0.16[h]	65.6 ± 0.64[i]	73.0 ± 0.92[i]	-11.3 ± 0.55[e]
Mung bean	72.1 ± 0.09[b]	73.7 ± 0.32[h]	76.9 ± 0.56[d]	+ 1.1 ± 0.12[i]
Banana	72.2 ± 0.23[b]	76.9 ± 0.35[c]	83.2 ± 0.36[b]	-15.7 ± 0.62[c]
Cassava (M4)	67.3 ± 0.52[f]	71.1 ± 0.65[f]	78.3 ± 0.03[h]	-13.9 ± 0.14[d]
Cassava (Sree Jaya-short duration)	67.5 ± 0.41[f]	71.8 ± 0.31[d]	80.7 ± 0.12[g]	-24.5 ± 0.00[a]
Sweet potato (Sree Arun)	68.8 ± 0.05[e]	73.2 ± 0.21[gf]	77.7 ± 0.36[e]	-9.6 ± 0.58[f]
Sweet potato (Sree Kanaka-carotene rich variety)	72.1 ± 0.26[b]	77.2 ± 0.03[b]	82.5 ± 0.25[b]	-13.7 ± 0.29[d]
Arrowroot	74.3 ± 0.23[a]	78.2 ± 0.64[a]	84.0 ± 0.29[a]	-14.1 ± 0.55[d]
Potato	69.2 ± 0.32[d]	72.7 ± 0.87[gf]	78.0 ± 0.65[f]	-6.5 ± 0.54[h]

[1]Values presented are the mean of three replications

[2]Mean values in each column with different letters in the superscript are significantly different

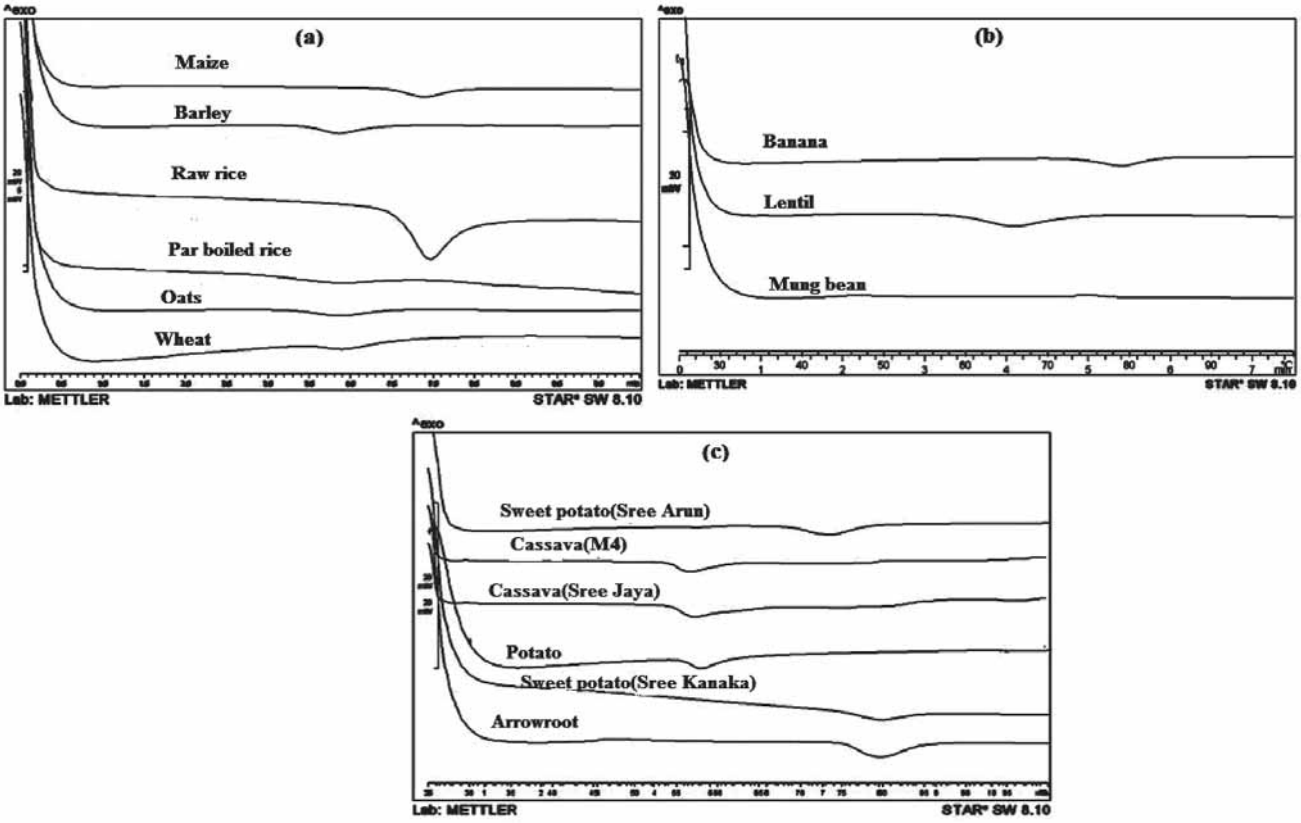

Fig. 2. DSC thermograms of (a) cereal starches, (b) pulses and banana starch and (c) tuber starches

Table 4. Water binding capacity (WBC) of starch from different sources

Sample	WBC (%)
Barley	84.4 ± 0.08[b]
Oats	81.0 ± 0.07[b]
Wheat	85.9 ± 0.14[b]
Par-boiled rice	87.2 ± 0.98[a]
Raw rice	83.2 ± 0.65[b]
Maize	64.5 ± 0.11[b]
Lentil	84.4 ± 0.21[b]
Mung bean	86.5 ± 0.11[b]
Banana	76.3 ± 0.00[b]
Cassava (M4)	80.5 ± 0.12[b]
Cassava (Sree Jaya-short duration)	72.0 ± .03[b]
Sweet potato (Sree Arun)	79.1 ± 0.21[b]
Sweet potato (Sree Kanaka-carotene rich variety)	77.4 ± 0.00[b]
Arrowroot	69.6 ± 0.09[b]
Potato	80.9 ± 0.12[b]

[1]Values presented are the mean of three replications
[2]Mean values in each column with different letters in the superscript are significantly different

Table 5. The *in vitro* digestibility of different starches after incubation with porcine pancreatic amylase

Starch sample	*In vitro* starch digestibility (%)	
	30 min	60 min
Barley	45.1 ± 3.21[d]	62.6 ± 2.65[de]
Oats	45.13 ± 1.36[d]	60.89 ± 2.74[e]
Wheat	51.23 ± 2.98[c]	71.69 ± 1.98[b]
Par-boiled rice	30.38 ± 3.54[h]	54.19 ± 2.0[f]
Raw rice	29.67 ± 1.85[h]	43.89 ± 3.12[h]
Maize	54.7 ± 1.20[bc]	67.9 ± 0.97[bc]
Lentil	37.2 ± 1.40[g]	46.1 ± 1.30[gh]
Mung bean	37. 9 ± 1.15[gf]	47.3 ± 0.98[g]
Banana	39.1 ± 1.12[efg]	54.0 ± 1.19[f]
Cassava (M4)	40.3 ± 1.25[def]	60.4 ± 0.98[e]
Cassava (Sree Jaya-short duration)	42.9 ± 1.11[de]	62.0 ± .80[de]
Sweet potato (Sree Arun)	53.2 ± 1.56[bc]	66.0 ± 0.76[cd]
Sweet potato (Sree Kanaka-carotene rich variety)	56.12 ± 1.96[b]	70.12 ± 1.23[bc]
Arrowroot	63.0 ± 1.23[a]	78.1 ± 1.22[a]
Potato	27.2 ± 0.75[h]	37.3 ± 2.14[i]

[1]Values presented are the mean of three replications
[2]Mean values in each column with different letters in the superscript are significantly different

In vitro starch digestibility

The *in vitro* digestibility of different starches after 30 and 60 minutes of incubation with Porcine Pancreatin are presented in Table 5. The digestibility varies with the botanical source of starch. During the first 30 minutes of enzyme incubation, the % digestibility was highest for arrowroot starch (63.0 ± 1.23%) and lowest for potato starch (27.2 ± 0.75%). Banana and legume starches showed moderate levels of digestibility (39 and 37% respectively). The trend was almost similar after 60 minutes of enzyme incubation also, with the highest % digestibility observed for arrowroot starch (78.1%) and lowest for potato starch (37.3%). According to Hu et al. (2004) the *in vitro* starch digestibility of rice varieties varies with amylose content. In the present study also the starch digestibility was found to depend on amylose content. Correlation analysis showed that % digestibility and amylose content in the starch are negatively correlated (r = - 0.41 at 30 min and r = -0.57 at 60 min of enzyme incubation) and the starch samples with higher amylose content exhibited lower digestibility. This could be because the retrograded amylose becomes resistant to digestive enzymes. Williamson et al. (1992) reported that wheat starches hydrolysed faster than potato and banana starches by porcine pancreatic amylase and it might be due to the higher granular size and greater crystalline structure (Ring et al., 1988; Gallant et al., 1992). Dreher et al. (1984) and Benmoussa et al. (2004) reported a higher enzymatic digestibility for cereal starches compared to legume and tuber starches. In the present study, this holds good in the case of starches from legumes and potato, but for tropical tuber starches enzymatic digestibility was higher than cereals.

RDS, SDS and RS contents

In general, tuber starches and cereal starches possess lower rapidly digestible starch (RDS) content than those in pulses (Table 6). The lowest RDS content was exhibited by barley starch (69.5%), whereas maize, oats, lentil and mung bean starches showed comparatively higher RDS (95.0, 93.7, 93.9 and 94.4% respectively). Pulse and maize starches showed lower SDS contents (0.15-0.8%) than other

Table 6. Rapidly digestible (RDS), slowly digestible (SDS) and resistant starch (RS) contents in different starches

Sample	RDS	SDS	RS
		(%)	
Barley	69.5 ± 0.40^{i}	27.3 ± 0.46^{a}	3.2 ± 0.06^{cd}
Oats	93.7 ± 0.21^{b}	5.1 ± 0.14^{i}	1.3 ± 0.35^{g}
Wheat	70.97 ± 0.0^{h}	26.3 ± 0.0^{b}	2.7 ± 0.01^{de}
Par-boiled rice	78.9 ± 0.77^{ef}	18.5 ± 0.67^{f}	2.7 ± 0.09^{de}
Raw rice	74.2 ± 0.26^{g}	23.4 ± .41^{d}	2.2 ± 0.14^{def}
Maize	95.2 ± 0.13^{a}	0.15 ± 0.06^{j}	4.7 ± .07^{ab}
Lentil	93.9 ± 0.0^{b}	0.8 ± 0.00^{j}	5.3 ± 0.00^{a}
Mung bean	94.4 ± .28^{ab}	0.54 ± .08^{j}	5.1 ± .19^{a}
Banana	81.6 ± 0.0^{d}	15.1 ± 0.0^{g}	3.3 ± 0.0^{cd}
Cassava (M4)	79.4 ± .84^{e}	18.5 ± 0.25^{f}	2.1 ± 1.08^{efg}
Cassava (Sree Jaya-short duration)	78.2 ± 1.05^{f}	20.3 ± 0.53^{e}	1.6 ± .48^{gf}
Sweet potato (Sree Arun)	82.5 ± .59^{d}	14.2 ± 0.21^{g}	3.3 ± 0.38^{cd}
Sweet potato (Sree Kanaka-carotene rich variety)	73.5 ± 0.28^{g}	25.0 ± 1.13^{c}	1.6 ± 0.85^{gf}
Arrowroot	77.8 ± 0.33^{f}	20.2 ± 0.23^{e}	2.0 ± 0.09^{efg}
Potato	86.5 ± .86^{c}	10.5 ± 0.54^{h}	4.0 ± .035^{bc}

[1]Values presented are the mean of three replications
[2]Mean values in each column with different letters in the superscript are significantly different

starches. The slowly digestible starch was highest in barley starch (27.3%). The SDS was lower for potato starch (10.5%) in comparison to tropical tuber starches, which exhibited fairly higher SDS contents (14.2-25.0%). In cereal family, maize and oats starches showed an exception with lower SDS values. Starches from pulses viz., mung bean and lentil had the highest resistant starch (RS) content (5.1 and 5.3% respectively) among the starch samples. Maize starch had the highest RS content of 4.7% among the cereal starches followed by barley (3.2%). Starch from the cream fleshed variety of sweet potato (Sree Arun) and raw banana also showed a higher RS content (3.3%). All the tropical tuber starches showed lower RS content (1.6 to 3.3%) than potato starch (4.0 %). Sweet potato starch showed higher RS for white fleshed variety, whereas higher SDS for orange fleshed variety; both are preferable in dietetic applications. Barley starch also exhibited high RS and SDS contents. Brighentit et al. (1998) reported that cereals showed lower RS content compared to potato and legumes. In the present study also, it was found true with an exception of maize which has slightly higher RS value than potato starch, which could be due to varietal differences. Legume starches, which have higher amylose content has been reported to show higher RS content than corn (Chung et al. 2009), cereals and tuber starches (Yadav et al. 2010), which is in agreement with our results. Brighentit et al. (1998) reported that in the case of rice varieties, method of cooking and variety of rice strictly controls the RS level. According to the report of Katayama et al. (2011) cooked sweet potato possess RS in the range of 1.8-9.5% and potato and maize possessed RS ranging from3.5-5.2%, which was in agreement with the results of the present study.

A significant positive correlation of RDS ($p < 0.05$, r = 0.58) with amylose content was observed, i.e., RDS increased with increase in amylose content. RDS is the starch digested in first 20 minutes of enzyme incubation, wherein the amorphous amylose fraction gets easily attacked by the digestive enzyme. RS also showed significant positive correlation to amylose content with a correlation coefficient of 0.73. The retrograded amylose fraction might be responsible for the increased RS levels. This supports the observation of lower *in vitro* digestibility with higher amylose content. SDS had a negative correlation with amylose content ($p < 0.05$, r = -0.63). This is again due to the formation of recrystallised amylose during retrogradation.

Conclusion

A comparative study on the resistant starch content and digestibility pattern of starch from different botanical sources were carried out along with other physiochemical properties. On considering the digestibility profile, starches with higher amylose content exhibited lower *in vitro* digestibility and higher RS content due to the formation of crystallized amylose. The study showed that legume, maize and potato starches are good sources of resistant starch. Banana, barley and cream fleshed sweet potato starches also showed higher RS content coupled with good amount of slowly digestible starch. The starch from carotene rich sweet potato showed higher amounts of SDS. Hence, these starches can be exploited for developing novel functional foods with low calorific value. But the applicability of these natural RS sources is yet to be studied in detail regarding the stability of the RS during various modifications and cooking operations.

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