Characterization of modified pearl millet (*Pennisetum typhoides*) starch

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Abstract Pearl millet starch (*Pennisetum typhoides*) was isolated and subjected to hydrothermal, acidic and enzymatic modifications. Native and various modified starches were characterized in terms of yield, moisture, protein, ash, bulk density, swelling power, solubility, colour, sediment volume, gel consistency, water binding capacity, pasting properties, freeze thaw stability and paste clarity. Hydrothermal modification (HTMS) caused an increase in swelling power and solubility. L value was higher for acid and enzymatically modified starches (EMS). A significant reduction ($p \leq 0.05$) in sediment volume and water binding capacity was observed for acid modified starch (AMS) and EMS. Peak viscosity values declined for all modifications. However, EMS and AMS showed an improved freeze-thaw stability and paste clarity.

Keywords Pearl millet · Starch · Modification · Hydrothermal · Acid · Enzymatic

Introduction

The cooking of native starch loses clarity, forms gel and undergoes syneresis during storage due to retrogradation. This phenomenon deteriorates the quality of food products and restricts its functionality. Starch modification is often used to circumvent these limitations. In modifications, starch is tailor made to meet the requirements of the end-user, giving rise to a

range of specialty products. Starch modification is a process of altering the starch structure by affecting the hydrogen bond in a controllable manner. Usually, starch degradation can be done by several methods such as physical alteration, chemical degradation enzymatic modification or genetic transformation (Yiu et al. 2008). During hydrothermal modification, starch properties are modified through controlled application of heat and moisture which produces physical modifications within the starch granules. Gelatinization and damage to the starch granules with respect to size, shape or birefringence do not occur due to the controlled application of heat/moisture (Stute 1992). Many types of chemical modifications include acid hydrolysis (Singh and Ali 2000), oxidation (Parovuori et al. 1995), etherification (Adebowale and Lawal 2003), etherification and cross-linking (Seidel et al. 2004), acid-alcohol treatment (Yiu et al. 2008) etc. is in practice. Pearl millet (*Pennisetum typhoides*), a hardy cereal crop compared with wheat and rice, is grown in regions with relatively low rainfall owing to its ability to tolerate and survive under continuous or intermittent drought. The crop is being processed by the age old traditional methods (Jain and Bal 1997), but can be used to prepare novel foods. It is a low cost and easily available source of starch. The pearl millet starch may be a substitute for corn starch (Abdalla et al. 2009). The present study was undertaken to optimize the process conditions for starch isolation and also to investigate the behaviour of native and modified starches as affected by different modifications.

Materials and methods

Raw materials

Freshly harvested pearl millet grains were purchased from local grain market and stored at ambient temperature (28–32±

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2 °C) in gunny bags during experimentation period and immediately used for starch isolation. All chemicals used in the analysis were of analytical grade (SD Fine-Chem Limited, Mumbai, India). A commercial hammer mill (Bells India Instrumentation, New Delhi) was used to grind the manually cleaned and graded pearl millet grains. The ground material was passed through 100 µm sieve to be used for starch isolation.

Starch isolation

Steeping of flour (100 µm) was done with 0.1%, 0.2%, 0.3% NaOH (1:6 w/v) containing 0.2% NaHSO₃ based on water and kept at 45 °C in a water bath for 90 min with continuous stirring. Centrifugation at 3,000 rpm was done (Eltek Centrifuge, MP 400 R, Electrocraft, Mumbai, India) for 15 min. Top brown protein layer was removed by discarding and the white starch was resuspended in distilled water and centrifuged and decanted until there was no longer any visible protein (brown) layer present (Qian et al. 1998). Final starch was resuspended in distilled water. The initial pH of starch dispersion was 9.2 and adjusted to a pH range of 6.5–7.0 using 1 M HCl. The starch was filtered through buchner funnel under vacuum and subjected to drying at 50 °C for 12 h. The dried starch cake was ground using pestle and mortar, passed through 75 µm sieve and stored in LDPE bags (90 µm) at ambient temperature (30±2 °C) till further use. The percent yield was calculated by multiplying the ratio of starch obtained and flour used for starch isolation with 100.

Starch modification

Isolated native starch (NS) was subjected to three different types of modifications viz., hydrothermal, acidic and enzymatic methods.

Hydrothermal modification

Starch, conditioned to 25–28% moisture content (dry basis) was sealed in LDPE bags and kept at 4–6 °C for 8 h to equilibrate the moisture throughout. Starch sample was taken out of the LDPE bags and placed in a covered baking pan for 3 h at 110 °C. The baking pan containing the sample was shaken occasionally for even distribution of heat and then cooled to room temperature followed by drying at 50 °C and sealed in polyethylene bags (Collado et al. 2001).

Acid modification

Starch slurry was prepared by dispersing starch (40 g) in 0.14 mol equivalent/L (0.14 N) of aqueous hydrochloric acid.

The reaction was allowed for 8 h in a water bath at 50 °C and slurry was adjusted to pH 5.5 with 1 mol equivalent/L NaOH and the slurry was washed thrice with deionized water and the pH was checked for chloride ions using litmus paper prior to filtration. Starch was dried overnight in a convection oven at 50 °C (Wang and Wang 2001).

Enzymatic modification

Crude fungal amylase (0.1%) derived from *Aspergillus oryzae* having enzyme activity 2,000 U/kg was used (Hood and Arneson 1975). Starch–enzyme suspension was incubated at 37 °C for 90 min in 0.04 M acetate buffer at pH 4.7.

Starch characterization

Physico-chemical analysis

Starch recovery was expressed as percent yield. The moisture, ash and protein were determined using standard procedures (AOAC 1995). Bulk density was determined as per the method as described (Balandrán-Quintana et al. 1998).

Solubility and swelling power

Starch (0.6 g) was heated with 40 ml of water at 60 °C for 30 min. Lump formation was prevented by stirring. The dispersion was centrifuged at 3,000 rpm for 15 min. Supernatant was carefully removed and starch sediment was weighed. An aliquot of supernatant (5 ml) was taken in pre-weighed petri dish and evaporated for 2 h at 130 °C and then weighed. The residue obtained after drying of supernatant represented the amount of starch solubilized in water (Subramanian et al. 1994; Raina et al. 2006). The result was expressed as:

$$\text{Solubility (\%)} = \frac{W_{ss} \times 100}{W_s}$$

Here, W_{ss} is the weight of soluble starch (g) and W_s is the weight of the sample (g).

$$\text{Swelling power (\%)} = \frac{W_{sp}}{W_s \times (100 - \% \text{ solubility})} \times 100$$

Here, W_{sp} is the weight of sediment paste (g) and W_s is the weight of sample (g).

Sediment volume

Starch (1 g) was mixed with 95 ml of distilled water. The pH of starch slurry was adjusted to pH 7.0 using 5% NaOH/HCl followed by heating in a boiling water bath for 15 min. Distilled water was added to make the total weight

to 100 g. The mixture was transferred to a 100 ml graduated cylinder and was sealed. The starch slurry was kept at room temperature for 24 h and volume of sediment consisting of starch granules was measured (Tessler 1978).

Colour determination

Colour was measured by CR-300 chroma meter (Minolta, Japan), as colour L, a, and b values. L value represents lightness, +/- a value represent redness/greenness, and +/- b value represent yellowness/blueness axis. White and black tiles provided with the chroma meter were used as standard.

Gel consistency

Starch samples (0.1 g, dry basis) were wetted in a test tube (16×150 mm) with 0.2 ml of 95% ethanol containing 0.025% bromothymol blue and dispersed in 2 ml of 0.2 N KOH. The tubes were heated in a vigorously boiling water bath for 8 min, cooled at room temperature for 5 min followed by cooling in an ice water bath for 20 min and then laid down horizontally for 1 h at room temperature. Longer the gel travel within tube implies the, lower consistency (Yadav et al. 2006).

Water binding capacity

Water binding capacity was determined using the method described (Yamazaki 1953; Medcalf and Gilles 1965). A suspension of 5 g starch (dry basis) in 75 ml distilled water was agitated for 1 h and centrifuged at 3,000 rpm for 10 min and excess water was drained for 10 min and then weighed.

$$\text{Water binding capacity (\%)} = \frac{W_{rs} \times 100}{W_s}$$

Here, W_{rs} is the weight of residual starch (g) and W_s is the weight of sample (g).

Pasting properties

Rapid Visco-Analyzer (Newport Scientific Pvt. Ltd., Warriewood, Australia) was used to determine the pasting properties of starch. A suspension of 3 g starch (14% moisture) in 25 ml of distilled water underwent a controlled heating and cooling cycle under constant shear. Sample was held at 50 °C up to 1 min. Samples were heated (50–95 °C, 12 °C/min) and held at 95 °C for 5 min. Subsequently, samples were cooled (50 °C, 12 °C/min) and held at 50 °C for 5 min. A RVA plot of viscosity (cP) versus time (s) was used to determine peak viscosity (PV), trough (T), breakdown (BD), final viscosity (FV), set back (SB), peak time (P_{time}) and peak temperature (P_{temp}).

Table 1 Physico-chemical characteristics of native and modified pearl millet starches

Sample	Moisture content (%)	Protein (%)	Ash (%)	Bulk density (g/mm ³)	Swelling power (%)	Solubility (%)	Colour value			Sediment volume (ml)	Water binding capacity (%)	Gel consistency (mm)
							L	a	b			
NS	4.5 ^c ±0.42	2.04 ^d ±0.12	1.35 ^c ±0.50	0.52 ^d ±0.04	3.80 ^c ±0.09	16.09 ^c ±0.59	78.58 ^b ±0.26	0.53 ^a ±0.04	12.53 ^c ±0.14	1.5 ^c ±0.09	291.8 ^c ±0.64	92.5 ^b ±17.68
HTMS	4.3 ^a ±0.14	1.76 ^b ±0.49	1.14 ^a ±0.41	0.44 ^b ±0.03	4.26 ^d ±0.29	17.08 ^d ±2.95	74.16 ^a ±0.57	2.38 ^d ±0.03	16.48 ^d ±0.06	1.5 ^d ±0.29	310.8 ^d ±4.59	120 ^d ±0.00
AMS	5.0 ^d ±0.0	1.78 ^c ±0.25	1.14 ^a ±0.17	0.37 ^a ±0.01	3.64 ^a ±0.22	11.92 ^a ±1.29	82.97 ^d ±0.16	1.03 ^c ±0.04	7.92 ^b ±0.19	0.5 ^a ±0.22	253.7 ^a ±20.08	62.5 ^a ±10.61
EMS	4.5 ^b ±0.14	1.51 ^a ±0.12	1.28 ^b ±1.74	0.48 ^c ±0.02	3.77 ^b ±0.45	14.17 ^b ±2.83	81.69 ^c ±0.16	0.92 ^b ±0.05	7.16 ^{a+} ±0.09	0.5 ^b ±0.45	258.2 ^b ±0.35	105 ^c ±21.21

NS Native Starch, HTMS Hydrothermally modified starch, AMS Acid modified starch, EMS Enzyme modified starch

Values are means of triplicate replications ± standard deviation

Values with different superscripts vary significantly at $p \leq 0.05$

Freeze thaw stability

Aqueous suspension of starch (5%, w/w) was heated at 95 °C under constant agitation for 1 h. The paste was weighed (20 g) into previously weighed centrifuge tubes and capped tightly. It was centrifuged (1,000 rpm, 10 min) to remove free water. The supernatant was decanted and tubes containing starch paste were subjected to eight freeze thaw cycles followed by centrifugation (4,000 rpm, 30 min). Alternate freezing and thawing was performed by freezing for 24 h at −18 °C and thawing for 4 h at 30 °C. The percent water separated after each freeze thaw cycles was measured (Kaur et al. 2004) in terms of syneresis.

$$\text{Syneresis (\%)} = \frac{W_{H_2O} \times 100}{W_s}$$

Here, W_{H_2O} is the water separated (g) and W_s is the weight of the sample (g).

Paste clarity

Light transmittance (%) of pastes from starches was measured (Craig et al. 1989; Perera and Hoover 1999). A 2% (dry basis) aqueous suspension of starch was heated in boiling water bath for 30 min with constant stirring. The suspension was cooled to room temperature. Samples were stored for 5 days at 4 °C, and transmittance was measured at an interval of 24 h for 5 days at 640 nm against a water blank using UV–VIS Spectrophotometer (Lab India UV 3000, Lab India Instruments Pvt. Ltd., Mumbai, India).

Statistical analysis

Data were analyzed for analysis of variance ANOVA and Duncan's multiple range test (DMRT) using SPSS version 16.0.

Results and discussion

Proximate composition

Yield of pearl millet starch was found to be 53.1% (net flour basis). Yield of 56.1% and 57.5% has been reported for millet starch in literature (Malleshi et al. 1986; Wankhede et al. 1979). The physico-chemical characteristics of native and modified pearl millet starch are given in Table 1. Native pearl millet starch (NS) had moisture content of 4.5% (db). The modified starch samples had lower residual protein and ash contents. Protein content values were found to be similar for AMS (acid modified starch) and HTMS (hydrothermally modified starch). Protein content was determined as 1.51% for EMS (enzymatically modified starch). Ash content was higher for NS than the modified starches.

Bulk density

Bulk density of NS was found to be 0.52 g/mm³. In literature, pearl millet starch had a bulk density 0.63 g/mm³ (Abdalla et al. 2009). The modifications had comparatively lower values of bulk density as compared to NS ($p \leq 0.05$) (0.37–0.48 g/mm³).

Swelling power

NS had swelling power of 3.8%. HTMS showed an increase in swelling power (4.26%) however AMS and EMS gave a lower swelling power (3.64% and 3.77%) followed by AMS (3.64%) and EMS (3.77%). Swelling power is contributed by amylopectin content (Tester and Morrison 1990) and also the topochemical aspects (distribution across the granule, amylose/amylopectin distribution) (Heeres et al. 1998). Higher swelling power of pearl millet starch was observed probably due to longer chains in amylopectin structure (Sasaki and Matsuki 1998). Increase

Table 2 Pasting characteristics of native and modified pearl millet starches

Sample	RVA parameters (cP)						
	PV	T	BD	FV	SB	P _{time} (min)	P _{temp} (°C)
NS	2708 ^d	1124 ^b	1583.5 ^d	4353 ^c	3229 ^a	4.930 ^b	84.15 ^b
HTMS	2337 ^b	980 ^a	1356.0 ^c	5460 ^d	4480 ^a	4.835 ^a	81.63 ^a
AMS	2441 ^c	1787 ^d	760.0 ^b	3809 ^b	2022 ^a	5.435 ^c	87.03 ^c
EMS	2225 ^a	1707 ^c	518.0 ^a	3409 ^a	1702 ^a	5.500 ^d	87.10 ^d

NS Native Starch, HTMS Hydrothermally modified starch, AMS Acid modified starch, EMS Enzyme modified starch

PV peak viscosity; T trough viscosity; BD breakdown; FV final viscosity; SB set back viscosity; P_{time} (min) = peak time; P_{temp} (°C) = peak temperature

Values with different superscripts vary significantly at $p \leq 0.05$

in starch crystallinity after modification might have restricted the percolation of water within starch matrices (Hoover and Manuel 1996) causing reduced swelling power for AMS and EMS.

Solubility

Solubility corresponds to hydrophilicity and amylose content i.e. more the dissociation of inter and intra hydrogen bonds, more will be the amylose leaching and hence solubility (Lawal 2009). Starch molecules imbibed water as the temperature rises. The amylose and linear branches of amylopectin dissociate in suspension and increase the solubility of starch. Solubility ranged from 11.92% (AMS) to 17.08% (HTMS). NS and EMS however had intermediate values i.e. 16.09% and 14.17%, respectively. Maximum value of HTMS showed a maximum hydrophilicity and minimum leach out of linear molecules. AMS had also undergone minimum dissociation corresponding to lesser hydrophilicity and minimum leach out. However, in EMS leaching of linear molecules was to a lesser extent and hence had lower solubility. The result showed that HTMS have weaker inter and intra molecular hydrogen bond. However, AMS resisted the leaching comparatively to a greater extent and are structurally strong and hence are least soluble.

Colour

EMS and AMS had significantly ($p \leq 0.05$) higher L (81.69, 82.97) and lower b values (7.16, 7.92), respectively. Higher colour values for AMS may be due to the effect of acid that lead to smaller particle size and thus higher refractive index. HTMS had the highest a and b values. This may be attributed to the change in colour caused by Maillard reaction between reducing sugar from the heated starch and the amino group in the proteins during modification (Lorlowhakam and Naivikul 2006). Increased a and b colour values have been reported for japonica milled heat moisture treated rice flour (Takahashi et al. 2005).

Sediment volume

Sediment volume indicates the changes in starch molecular association during the process of modification (Yadav et al. 2007) which also depends on the type of modification. It also indicates the degree of cross linking in starch. Sediment volume of NS and HTMS was found to be 1.5 ml. AMS and EMS showed a significantly ($p \leq 0.05$) lower sediment volume. It has also been reported that the acetylated and enzymatic modification lowered the sediment volume of potato and sweet potato flours (Yadav et al. 2007).

Fig. 1 Effect of freeze-thaw cycles on syneresis in native and modified pearl millet starches. (NS Native starch, HTMS hydrothermally modified starch, AMS acid modified starch, EMS enzymatically modified starch). Values are means of triplicate replications ($n=3$)

Water binding capacity

Water binding capacity had a higher value for HTMS (310%) and significantly ($p \leq 0.05$) lower value for AMS (253.7%) and EMS (258.2). The difference in availability of water binding sites in modified starch among the various samples lead to this variation in water binding capacity (Wotton and Bamuarachchi 1978; Abraham 1993).

Gel consistency

More the distance traveled by the starch gel, lower is the gel consistency. EMS showed a significantly ($p \leq 0.05$) higher gel consistency (travel distance, 105 mm). HTMS showed a lower gel consistency (travel distance, 120 mm). It was noticed that the gel consistency is proportional to the sediment volume of aqueous starch dispersion (Unnikrishnan and Bhattacharya 1981) at room temperature.

Fig. 2 Effect of storage time on transmittance of native and modified pearl millet starches. Values are means of triplicate replications ($n=3$)

Pasting characteristics

Table 2 shows the pasting characteristics of native and modified pearl millet starches. The peak viscosity for NS was 2,708 cP. The maximum viscosity was attained at the most swollen state of starch granules. Continued heating of paste beyond this point caused the granule to rupture and accompanied by the fall in viscosity (Kearsley and Sicard 1989). The secondary increase in viscosity (setback) during the cooling phase which is associated with the retrogradation phenomenon and related to amylose content was observed to be minimum for EMS (1,702 cP) as compared to NS (3,229 cP). The final viscosity of NS was found to be 4,353 cP. AMS and EMS had a comparatively lower breakdown (760.0 cP and 518.0 cP) and higher trough (1,787 cP and 1,707 cP), while HTMS gave lower pasting properties viz. peak viscosity of 2,337 cP, trough of 980 cP and breakdown of 1,356 cP, but higher final viscosity of 5,460 cP and setback of (4,480 cP) respectively. Lower peak viscosity indicates lower water binding capacity of the starch (Sekine 1996), which is similar to EMS that showed significantly ($p \leq 0.05$) lower water binding capacity.

Freeze thaw stability

Figure 1 shows the freeze thaw stability of native and modified pearl millet starches in terms of syneresis. Syneresis increased with the number of freeze thaw cycles. Repeated freeze thaw cycle or low temperature treatment of concentrated pastes gives rise to cryotropic gel formation with like textured food product (Lozinsky et al. 2000). This phenomenon also results in phase separation and ice growth as starch is syneresised and water is separated from gel (Eliasson and Kim 1992). Maximum syneresis was observed in HTMS. In earlier studies, increase in hydrophilic and hydrophobic tendency of millet starch has been observed with increasing level of hydrothermal treatment (Adebowale et al. 2005). Acid and enzymatic modification resulted in decrease in syneresis. Least syneresis was exhibited by EMS at the end of eight freeze thaw cycle. Reduction in inter chain bonding between starch molecules in modified starch could be a reason for the fall in syneresis (Lawal 2009).

Paste clarity

Paste clarity (% transmittance) was found to decrease for all the samples with the storage period (Fig. 2). Similarly, the decrease in light transmittance with storage time was reported in literature (Achille et al. 2007). EMS and AMS exhibited comparatively better transmittance than HTMS and NS throughout the storage period. However, there is an increase in paste clarity after hydroxypropylation in finger millet (Lawal 2009) and maize starch (Liu et al. 1999). This

may be attributed to greater stability of starch structure after modification due to improvement of inter and intra molecular bonding. This behavior is essential in foods such as jellies and fruit pastes, to get desired consistency.

Conclusion

Pearl millet starch was isolated and modified by hydrothermal, acidic and enzymatic methods. The acid modified starch (AMS) and enzyme modified starch (EMS) showed improved color values, pasting characteristics, paste clarity and freeze thaw stability. Hydrothermally modified starch (HTMS) had high swelling power, solubility and water binding capacity. Thus, these modifications were effective in altering the characteristics of the starch that may meet the desired end uses. The studies are expected to add to the area of modification of starch from highly nutritious, low cost and under utilized pearl millet.

References

- Abdalla AA, Ahmed UM, Ahmed AR, El Tinay AH, Ibrahim KA (2009) Physicochemical characterization of traditionally extracted pearl millet starch (*Jir*). J Appl Sci Res 5:2016–2027
- Abraham TE (1993) Stabilization of paste viscosity of cassava starch by heat moisture treatment. Starch-Starke 45:131–135
- Achille TF, Georges ANG, Alphonse K (2007) Contribution to light transmittance modelling in starch media. Afr J Biotechnol 6:569–575
- Adebowale KO, Lawal OS (2003) Functional properties and retrogradation behaviour of native and chemically modified starch of mucuna bean (*Mucuna pruriens*). J Sci Food Agr 83:1541–1546
- Adebowale KO, Afolabi TA, Olu-Owolabi BI (2005) Hydrothermal treatments of finger millet (*Eleusine coracana*) starch. Food Hydrocoll 19:974–983
- AOAC (1995) Official methods of analysis, 16th edn. Association of Official Analytical Chemists, Arlington
- Balandrán-Quintana RR, Barbosa-Cánovas GV, Zazueta-Morales JJ, Anzaldúa-Morales A, Quintero-Ramos A (1998) Functional and nutritional properties of extruded whole pinto bean meal (*Phaseolus vulgaris* L.). J Food Sci 63:113–116
- Collado LS, Mabesa LB, Oates CG, Corke H (2001) Bihon-type of noodles from heat-moisture treated sweet potato starch. J Food Sci 66:604–609
- Craig SAS, Maningat CC, Seib PA, Hosney RC (1989) Starch paste clarity. Cereal Chem 66:173–182
- Eliasson AC, Kim HR (1992) Changes in rheological properties of hydroxypropyl potato starch pastes during freeze-thaw treatments. III. Effects of cooking conditions and concentration of the starch paste. J Texture Stu 23:279–293
- Heeres A, van Doren HA, Gotlieb KF, Bleeker IP, Kellogg RM (1998) Cross-linking of starch with bifunctional precursors of nitroalkenes. Carbohydr Res 310:191–201
- Hood LF, Ameson VG (1975) In-vitro digestibility of hydroxypropyl distarch phosphate and unmodified tapioca starch. Cereal Chem 53:282–290
- Hoover R, Manuel H (1996) The effect of heat-moisture treatment on the structure and physicochemical properties of normal maize,

- waxy maize, dull waxy maize and amylomaize V starches. *J Cereal Sci* 23:153–162
- Jain RK, Bal S (1997) Properties of pearl millet. *J Agric Eng Res* 66:85–91
- Kaur L, Singh N, Singh J (2004) Factors influencing the properties of hydroxypropylated potato starches. *Carbohydr Polym* 55:211–223
- Kearsley MW, Sicard PJ (1989) The chemistry of starches and sugars present in food. In: Dobbing J (ed) *Dietary starches and sugars in man: a comparison*. Springer, London
- Lawal OS (2009) Starch hydroxyalkylation: physicochemical properties and enzymatic digestibility of native and hydroxypropylated finger millet (*Eleusine coracana*) starch. *Food Hydrocoll* 23:415–425
- Liu HJ, Ramsden L, Corke H (1999) Physical properties and enzymatic digestibility of hydroxypropylated and normal maize starches. *Carbohydr Polym* 40:175–182
- Lorlowhakarn K, Naivikul O (2006) Modification of rice flour by heat moisture treatment (HMT) to produce rice noodles. *Kasetsart J (Nat Sci)* 40:135–143
- Lozinsky VI, Damshkaln LG, Brown R, Norton IT (2000) Study of cryostructuring of polymer systems. XVI. Freeze-thaw-induced effects in the low concentration systems amylopectin-water. *J Appl Polymer Sci* 75:1740–1748
- Malleshi NG, Desikacher HSR, Tharanathan RN (1986) Physico-chemical properties of native and malted finger millet, pearl millet and foxtail millet starches. *Starch-Starke* 38:202–205
- Medcalf DG, Gilles KA (1965) Wheat starches, comparison of physicochemical properties. *Cereal Chem* 42:558–568
- Parovuori P, Hamunen A, Forssell P, Autio K, Poutanen K (1995) Oxidation of potato starch by hydrogen peroxide. *Starch-Starke* 47:19–23
- Perera C, Hoover R (1999) Influence of hydroxypropylation on retrogradation properties of native, defatted and heat-moisture treated potato starches. *Food Chem* 64:361–375
- Qian J, Rayas-Duarte P, Grant L (1998) Partial characterization of buckwheat (*Fagopyrum esculentum*) starch. *Cereal Chem* 75:365–373
- Raina CS, Singh S, Bawa AS, Saxena DC (2006) Rheological properties of chemically modified rice starch model solutions. *J Food Process Eng* 29(2):134–148
- Sasaki T, Matsuki J (1998) Effect of wheat structure on swelling power. *Cereal Chem* 74:525–529
- Seidel C, Kulicke WM, He XC, Hartmann B, Lechner MD, Lazik W (2004) Synthesis and characterization of cross-linked carboxymethyl potato starch ether gels. *Starch-Starke* 56:157–166
- Sekine M (1996) Measurement of dynamic viscoelastic behavior of starch during gelatinization in xanthum-gum solution. *Nippon Shokuhin Kagaku Kogaku Kaishi* 43:683–688
- Singh V, Ali SZ (2000) Acid degradation of starch. The effect of acid and starch type. *Carbohydr Polymer* 41:191–195
- Stute R (1992) Hydrothermal modification of starches: the difference between annealing and heat/moisture-treatment. *Starch-Starke* 44:205–214
- Subramanian V, Hosney RC, Bramel-Cox P (1994) Shear thinning properties of sorghum and corn starches. *Cereal Chem* 71:272–275
- Takahashi T, Miura M, Ohisa N, Mori K, Kobayashi S (2005) Heat treatments of milled rice and properties of the flours. *Cereal Chem* 82:228–232
- Tester RF, Morrison WR (1990) Swelling and gelatinization of cereal starches I effects of amylopectin, amylose, and lipids. *Cereal Chem* 67:551–557
- Tessler MM (1978) Process for preparing cross-linked starches. US patent 4098997
- Unnikrishnan KR, Bhattacharya KR (1981) Swelling and solubility behaviour of parboiled rice flour. *J Food Tech* 16:403–408
- Wang L, Wang YJ (2001) Structures and physicochemical properties of acid-thinned corn, potato and rice starches. *Starch-Starke* 53:570–576
- Wankhede DB, Shehnaz A, Raghavendra R (1979) Preparation and physicochemical properties of starches and their fractions from finger millet (*Eleusine coracana*) and foxtail millet (*Setaria italica*). *Starch-Starke* 31:153–159
- Wotton M, Bamuarachchi A (1978) Water binding capacity of commercially produced native and modified starch. *Starch-Starke* 33:159–161
- Yadav AR, Guha M, Tharanathan RN, Ramteke RS (2006) Changes in characteristics of sweet potato flour prepared by different techniques. *Lebensm Wiss Technol* 39:20–26
- Yadav AR, Guha M, Reddy SY, Tharanathan RN, Ramteke RS (2007) Physical properties of acetylated and enzyme-modified potato and sweet potato flours. *J Food Sci* 72:249–253
- Yamazaki WT (1953) An alkaline water retention capacity test for the evaluation of cooking baking potentialities of soft winter wheat flours. *Cereal Chem* 30:242–246
- Yiu PH, Loh SL, Rajan A, Wong SC, Bong CFJ (2008) Physicochemical properties of sago starch modified by acid treatment in alcohol. *Am J Appl Sci* 5:307–311