RESEARCH ARTICLE

Slowly Digestible Sweetpotato Flour: Preparation by Heat-moisture Treatment and Characterization of Physicochemical Properties

Ji Hong Ahn, Hye Rim Baek, Kyung Mi Kim, Gui Jung Han, Jun Bong Choi, Yang Kim, and Tae Wha Moon

Abstract The preparation and physicochemical characteristics of sweetpotato flour with increased slowly digestible starch (SDS) fraction were investigated under various heat-moisture treatment (HMT) conditions. The optimum conditions for preparing slowly digestible sweetpotato flour established using response surface methodology were moisture content of 22%, temperature of 103°C, and treatment time of 5.8 h. The highest SDS content in heat-moisture treated sweetpotato flour was 57.6%. The relative crystallinity of heat-moisture treated sweetpotato flour decreased, but the X-ray diffraction pattern maintained the A-type. The DSC of the heat-moisture treated flour showed a decreased gelatinization temperature range and gelatinization enthalpy compared with native one. The viscosity profiles and values changed significantly with HMT, resulting in a higher pasting temperature, decrease of the viscosity values, and no breakdown. It indicates that heat-moisture treated sweetpotato flour is more stable at high temperatures and shear rates than native one.

Keywords: slowly digestible starch, sweetpotato flour, digestibility, heat-moisture treatment, response surface methodology

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Introduction

Starch, the most important reserve polysaccharide and the most abundant constituent of many plants, is the main source of digestible carbohydrates in human diet. Englyst *et al.* (1) classified starch into rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) based on the rate of glucose released during starch hydrolysis by digestive enzymes. RDS is the starch fraction that causes a sudden increase in blood glucose level after ingestion, and SDS is the starch fraction that is digested completely in the small intestine at a lower rate as compared to RDS. RS is the indigestible starch in small intestine, but it can be fermented in the large intestine.

Foods containing SDS may be advantageous in controlling and preventing diabetes. Such foods may also be helpful to satiety, physical performance, improved glucose tolerance, and reduced blood lipid levels in both healthy individuals and those with hyperlipidemia (2). Recently, studies have been reported on the development of SDS based on physical, chemical, and enzymatic methods (3-5). Heat-moisture treatment (HMT) of starches is defined as a physical modification that involves the treatment of starch granules at low moisture levels (<35% water, w/w) for a certain period of time (15 min-16 h) at high temperatures (84-120°C) (6). It changes the crystallographic pattern of the starch granules, inducing the conversion of a fraction of amorphous amylose to the crystalline form (7). Heat-moisture treated starches synthesized without any chemicals have almost similar paste stability and therefore have attracted the attention of the food industry (8).

Sweetpotato is one of the most important starch-producing crops in the world. Sweetpotato is rich in carbohydrates, vitamins, minerals, and dietary fiber, although its protein content is low (9). However, few studies have been carried out to improve the nutritional quality of sweetpotato flour

for the creation of value added products. Physical modification of flour has a high potential for the improvement of functional properties of sweetpotato flour and could help create new applications with the slow digestible property. In addition, flour is relatively easy to produce since the manufacturing process is simple, and therefore, it can contribute to the economical and effective mass production of various processed food products.

The objectives of this study were to establish the optimum HMT conditions for preparing sweetpotato flour with increased SDS content employing response surface methodology (RSM) and to investigate the physicochemical characteristics of heat-moisture treated sweetpotato flour.

Materials and Methods

Materials   A cultivar of sweetpotato, 'Daeyumi', was obtained from Bioenergy Crop Research Center, National Institute of Crop Science, Rural Development Administration, Korea. Amyloglucosidase (AMG 300L, activity 300 AGU/ mL) was purchased from Novozymes Inc. (Bagsvaerd, Denmark). Pancreatin (P-7545, activity 8×USP/g) and GOD-POD kit (BCS glucose kit) were purchased from Sigma-Aldrich (St. Louis, MO, USA), and BCS Corp. (Anyang, Korea), respectively.

Preparation of sweetpotato flour   Sweetpotato was peeled and crushed by a multi crusher (CR-481W; Samsung, Seoul, Korea). Sweetpotato flour was prepared by washing in distilled water 3 times, dried at 40°C in a forced-air oven, ground using a mortar and pestle, and passed through a 100 mesh sieve.

Experimental design for HMT   RSM was used to get the maximum SDS value through optimization of the production process of heat-moisture treated sweetpotato flours. In the current study, the Box-Behnken design was employed to understand the effects of moisture content, time, and temperature on the yield of SDS (10). The design scheme consisted of 15 treatments in which the central point was replicated 3 times to calculate the experimental error. A quadratic model containing 10 coefficients was used to describe the response of S, the content of SDS, using the following equation:

$$S=b_0+b_1X+b_2Y+b_3Z+b_{11}X^2+b_{22}Y^2+b_{33}Z^2$$
$$+b_{12}XY+b_{13}XZ+b_{23}YZ \qquad (1)$$

where, b_1, b_2, and b_3 are the regression coefficients that show the nature and extent of the response to the associate treatment conditions, and X, Y, and Z are the coded variables that are assigned to the moisture content, temperature, and time, respectively. Three levels of each

parameter (moisture, 18, 23, or 28%; temperature, 90, 110, or 130°C; and time, 1, 8, or 15 h) were used in the experimental design. The analysis was executed using SAS software (version 9.1; SAS Inc., Cary, NC, USA).

Heat-moisture treatment   The initial moisture content of the sweetpotato flour used was determined to be 7.2% according to the AACC method (11). The moisture content of the sweetpotato flour was brought to 18, 23, and 28% by adding appropriate amounts of distilled water into the glass containers. The samples were sealed in containers, and kept at room temperature for 24 h for equilibration. The heat treatment was performed in a forced air oven at 90, 110, or 130°C for 1, 8, or 15 h. Then, the containers were opened, and the samples were air-dried at room temperature to a moisture content of about 10%. The samples were then ground to pass through a 100 mesh sieve.

X-ray diffraction patterns and the degrees of relative crystallinity   X-ray diffraction analysis was performed with an X-ray diffractometer (model D5005; Bruker, Karlsruhe, Germany) (analysis parameters: 40 kV and 40 mA, CuKα radiation of 1.54Å wavelength, scanning through the 2θ range of 3-30° and step time of 4 s). Relative crystallinity was calculated according to the method of Nara and Komiya (12) using Origin 7.5 (Microbial, Northampton, MA, USA):

$$\text{Relative crystallinity (\%)}=\frac{A_c}{A_a+A_c} \times 100$$

where, A_a is the area of amorphous region and A_c is the area of crystalline region.

Gelatinization parameters   Gelatinization parameters were measured using a DSC (Phyris Diamond DSC; Perkin-Elmer Inc., Waltham, MA, USA). The calorimeter was calibrated with an indium standard. Distilled water (40 μL) was added with a micropipette to a sample (10 mg) in an aluminum DSC pan, which was then sealed, reweighed, and allowed to stand overnight at room temperature for moisture equilibration. The sample pan was heated from 30 to 120°C at 5°C/min with an empty pan as reference. Onset (T_0), peak (T_p), and conclusion (T_c) temperatures of gelatinization as well as gelatinization enthalpies (ΔH, J/g) were determined with the Pyris software.

Measurement of starch digestibility   Starch digestibility was determined following the method described by Englyst *et al.* (1) as modified by Shin *et al.* (5). Pancreatin (1 g) was added to 12 mL of water in a beaker and stirred using a magnetic stirrer for 10 min. This solution was centrifuged at 1,500×g for 10 min. A 10 mL volume of the cloudy supernatant was transferred to a volumetric flask

containing 0.2 mL amyloglucosidase solution and brought to 1.8 mL with distilled water.

For the determination of starch fraction, samples (30 mg, w.b.) were placed into 2-mL microtubes, 0.75 mL of sodium acetate buffer (0.1 M, pH 5.2) and a glass bead was added to each microtube. The microtubes were equilibrated in a shaking water bath with a stroke speed of 240 rpm at 37°C for 10 min. Prepared enzyme solution (0.75 mL) was then added to each microtube. The tubes were removed at 10 or 240 min, boiled to stop the reaction, and centrifuged at 5,000×g for 10 min. The glucose content of supernatant was measured using a GOD-POD kit (BCS glucose kit). RDS and SDS were measured after incubation with enzyme solution (pancreatin and amyloglucosidase) at 37°C for 10 and 240 min, respectively. RS was the starch not hydrolyzed after 240 min incubation.

Pasting properties The pasting properties were assessed using a rapid visco analyser (RVA-4; Newport Scientific Pty. Ltd., Warriewood, Australia). Each flour sample (2 g) was added to 25 mL of distilled water. The STD 1 profile (AACC method 76-21) was used. The flour slurries were heated from 50 to 95°C at 12°C/min and were then held at 95°C for 2.5 min. The pastes were cooled to 50°C at 12°C/min and finally maintained at 50°C for 2 min.

Swelling factor The swelling factor of heat-moisture treated flour was measured by the method of Tester and Morrison (13) with slight modification. Fifty mg of flour was suspended in 10 mL of distilled water and incubated in a water bath at 80°C for 30 min. This sample was cooled with cold water; 0.5 mL of blue dextran solution (5 mg/mL) was added. The sample was inverted to mix. After centrifugation at 3,000×g for 10 min, the absorbance of the supernatant was read at 620 nm.

Color measurement The color of sweetpotato flour was analyzed with a Minolta colorimeter (model CR300; Minolta Co., Osaka, Japan) using a (red=positive/green= negative), b (yellow=positive/blue=negative), and L (white =100/black=0) parameters of Hunter Lab system. The instrument was calibrated with a white plate (L=97.12, a= 0.18, b=1.75), and the total color difference, ΔE, was determined using the following equation:

$$\Delta E = (\Delta a^2 + \Delta b^2 + \Delta L^2)^{1/2}$$

where, Δa=a-a$_0$, Δb=b-b$_0$, ΔL=L-L$_0$, and $_0$ is the initial color value

Statistical analysis All experiments were performed in triplicate, and mean values and standard deviations (SD) are reported. Analysis of variance (ANOVA) was conducted and the mean separations were done by Duncan's multiple

range test ($p<0.05$). All the statistical analyses described above were conducted using SPSS for Windows 12.0 software (SPSS Inc., Chicago, IL, USA).

Results and Discussion

Establishment of optimal conditions Changes in starch structure and properties by HMT have been found to vary with starch source (6). Thus, the optimum conditions for preparation of sweetpotato flour with an increased amount of SDS could be diverse according to HMT conditions. In order to increase the formation of SDS, sweetpotato flour was heat-moisture treated, and RSM was used to optimize the treatment parameters. Basically, RSM relates product properties by using regression equations that describe interrelations between input parameters and product properties (14).

The portions of RDS, SDS, and RS were measured for the 15 treatment combinations shown in Table 1. Especially, the samples such as 3, 8, and 14, based on the experimental design, were triplicates of the central-point treatment. A regression analysis of the response variables showed that the experimental data fitted the quadratic model ($p<0.05$; Fig. 1). The model presented SDS % as a function of moisture (X), temperature (Y), and time (Z), as represented by Eq. 2 and shown in Fig. 1.

$$\text{SDS \%} = -291.122616 + 9.967405X + 4.518280Y$$
$$+ 2.223078Z - 0.168833X^2 - 0.022750XY - 0.019302Y^2$$
$$- 0.033571XZ - 0.007321YZ - 0.062670Z^2 \qquad (2)$$

The calculated digestibility gained from Eq. 2 using SAS software was 57.6%, and the optimized conditions were moisture content of 22%, temperature of 103°C, and treatment time of 5 h 48 min. This model was checked experimentally, and the experimental data (57.6%) presented little difference from the calculated data (58.5%). The values of SDS ranged from 31.5 to 56.5%. Therefore, the model conditions were regarded to be optimal for the development of SDS in heat-moisture treated sweetpotato flour. ANOVA indicated a high value of the regression coefficient (R^2=0.9772) from the model suggesting the exactness of the mathematical model (Table 3). From ANOVA, the factor with a high F-value and a low p-value indicates a great effect on the respective response variables. Accordingly, temperature which had the greatest F-value in ANOVA had the greatest effect on the SDS content. Moisture content and temperature had significant linear and quadratic effects ($p<0.01$) on SDS content, while time had only the quadratic effect ($p<0.05$) (data not shown). No significant interaction effect was observed ($p>0.05$). When RDS, SDS, and RS contents were considered all together, the increased proportion of SDS seemed to

Table 1. Contents of RDS, SDS, and RS under different HMT conditions

Sample	Responses[1]			Variables		
	RDS (%)	SDS (%)	RS (%)	Moisture (%)	Temperature(°C)	Time (h)
Native	19.0±1.7[2]	44.1±0.7	37.1±1.3			
1	31.3±0.9	35.5±1.1	33.2±0.1	23	130	15
2	34.4±1.2	43.0±2.2	22.6±1.7	28	110	15
3	16.0±0.8	55.0±0.4	28.9±1.0	23	110	8
4	13.7±0.8	52.6±0.7	33.7±0.7	23	90	1
5	17.5±1.3	51.8±1.0	30.4±1.0	18	110	1
6	15.8±1.1	51.8±1.5	32.6±0.8	18	90	8
7	17.9±1.9	50.6±1.5	31.5±1.2	28	90	8
8	14.5±1.7	56.5±1.6	29.0±0.2	23	110	8
9	32.2±1.0	48.5±2.0	19.4±1.2	28	110	1
10	19.8±1.1	51.0±1.6	29.1±0.5	18	110	15
11	9.4±0.3	47.8±1.4	42.8±1.1	23	90	15
12	36.8±1.4	44.4±1.6	18.8±2.1	23	130	1
13	22.5±1.3	41.8±0.5	35.7±1.8	18	130	8
14	16.4±0.8	56.1±0.4	27.2±1.0	23	110	8
15	47.1±1.0	31.5±1.1	21.4±1.1	28	130	8

[1]RDS, SDS, RS, and HMT indicate the rapidly digestible starch, slowly digestible starch, resistant starch, and heat-moisture treatment, respectively.
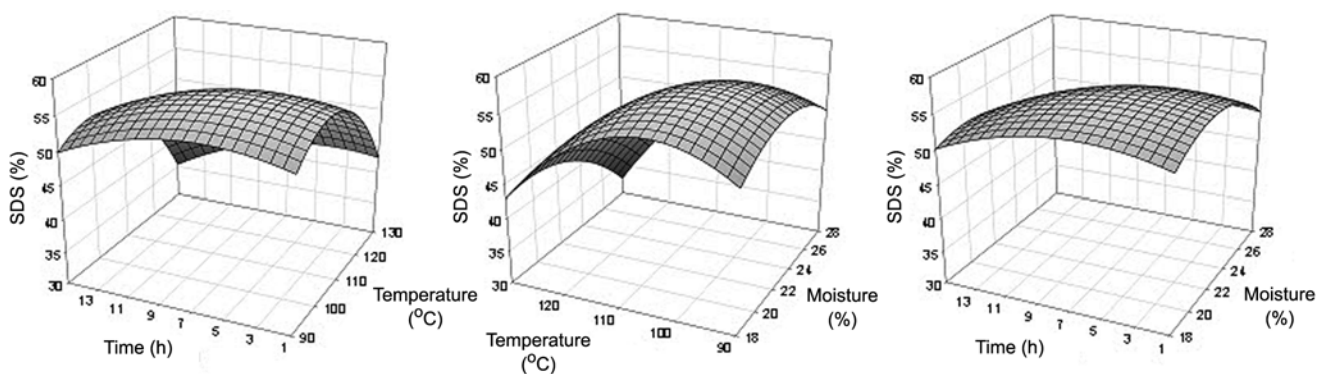[2]Data were expressed as mean±SD.

Fig. 1. Slowly digestible starch (SDS) response surface of heat-moisture treatment parameters of moisture content, temperature, and treatment time. The z axis is the response variable SDS%, and the x axis and y axis are the independent variables.

originate from RS fraction via HMT.

Digestibility of heat-moisture treated sweetpotato As shown in Table 1, the RS of the heat-moisture treated flour decreased as the moisture level or reaction temperature increased, whereas the contents of RDS and SDS increased compared with native samples. The increase in the RS fraction of sample 11 could be a result of partial association of amylose chains within the amorphous region, which would decrease accessibility to α-amylase (6). Sample 1 and 15 showed a decreased SDS and an increased RDS content. The increases in the RDS fractions indicated that they contained structures which can be more easily attacked by α-amylase, compared with other heat-moisture treated samples. It was due to higher temperature destroying the intermolecular structure of flour. The decrease in the

relative crystallinities and the gelatinization enthalpies followed the disruption of the starch granules (Table 4, 5). Gunaratne and Hoover (6) claimed that the initial step of α-amylolysis corresponds to the adsorption of α-amylase on the granule surface. Therefore, crystallite disruption near the granule surface upon HMT of true yam and potato starches could facilitate the rapid entry of α-amylase into the granule interior. The alteration of hydrothermally treated starch could induce an increase in the extent of amylolysis compared with that of native starch.

The influence of HMT on digestibility is decided by moisture content during HMT, reaction time and temperature, amylose-lipid interactions and amylose-amylose and/or amylose-amylopectin interaction (6,15). The increase in RDS and the decrease in SDS and RS levels in heat-moisture treated samples, such as 1 and 15, suggested that

Table 2. Optimum conditions for the formation of slowly digestible starch (SDS)

	SDS (%)	Moisture (%)	Temperature (°C)	Time (h)
Calculation[1]	57.6	22	103	5.8
Confirmation[2]	58.5	22	103	5.8

[1]Result from response surface methodology
[2]Result from the identified experiment

Table 3. Analysis of variance of the independent variables for the quadratic model

Variable	Sum of squares	Degree of freedom	Mean square	F-value	Pr>F	R^2
Moisture (X)	156.985	4	39.246	11.34	0.0101	
Temperature (Y)	552.528	4	138.132	39.92	0.0006	
Time (Z)	94.543	4	23.636	6.83	0.0293	
Linear	422.500	3		40.70	0.0006	0.5577
Quadratic	287.327	3		27.68	0.0015	0.3793
Crossproduct	30.428	3		2.93	0.1386	0.0402
Total model	740.254	9		23.77	0.0014	0.9772
Lack of fit	16.095	3	5.365	8.89	0.1028	
Pure error	1.207	2	0.603			
Total error	17.302	5	3.460			
Total model	R^2	0.9772				
	CV[1]	3.8867				

[1]Coefficient of variation

crystalline disruption resulted from HMT as evidenced by decreased crystallinity (Table 4) and gelatinization enthalpy (Table 5) (8,16,17).

The structural characteristic of SDS is an optimal mix of amorphous and semi-crystalline material. The crystalline regions are more resistant to enzyme hydrolysis, while the amorphous regions are more susceptible to that. A-type or B-type crystallite influences digestibility, mostly. Shorter double helices and their interior crystallites in A-type starches are more easily digestible and contain high amounts of RDS and SDS compared with B-type starches, which often contain a high amount of RS (18). In conclusion, the structural rearrangement in starch granules of sweetpotato flours by HMT caused the changes in flour digestibility and likely contributed to their slow digestion properties.

X-ray diffraction and relative crystallinity The X-ray diffraction patterns and relative crystallinities of the samples are shown in Fig. 2 and Table 4, respectively. The decrease of intensities and crystallinities indicated that the crystalline region of flour was disrupted by heat-moisture treatment. It has been suggested that the double helical movement during heat-moisture treatment could disrupt starch crytallinities and change crystalline orientation (6,19).

Changes in the X-ray diffraction pattern from C_a- to A-type have been noted in heat-moisture treated sweetpotato samples (5). However, other types of starches did not have an altered X-ray diffraction pattern after HMT, including taro, cassava (6), and cereal starches (20). Likewise, in this study, sweetpotato flour did not change the X-ray diffraction pattern of A-type. Only peak intensity and width was slightly changed by treatment condition. In addition, the starch crystalline peaks are noted to be affected by moisture content of the sample with ancillary effects on the relative crystallinity (21). Generally, crystalline patterns reflect molecular and structural organization of a sample (21). Besides, the crystalline type is determined by the combination of starch concentration and temperature. Hence, the change in relative crystallinity depends on the extent of melting during the heat treatment and the extent of recrystallization during cooling.

Large decreases in the swelling factor, gelatinization enthalpy, and relative crystallinity also indicate that the granular structure was disrupted to a great extent. These factors would bring out the increase in the RDS fraction and the decrease in RS in samples such as 1 and 15. Compared to native flour, sample Max did not show a significant difference in relative crystallinity, suggesting that its crystalline region was not disrupted by HMT.

The intensity and relative crystallinity of the peaks of heat-moisture treated samples at 17 and 18° were broader and lower than those of native sample (Fig. 2, Table 4). The X-ray diffraction pattern of sample 15 showed a broadening of most peaks (15, 17, and 21-23°) and a large decrease in relative crystallinity. The decreases of intensities and crystallinities mean that the crystalline region of flour was disrupted by hydrothermal treatment. On the other hand, relative crystallinity of sample 13 was higher than
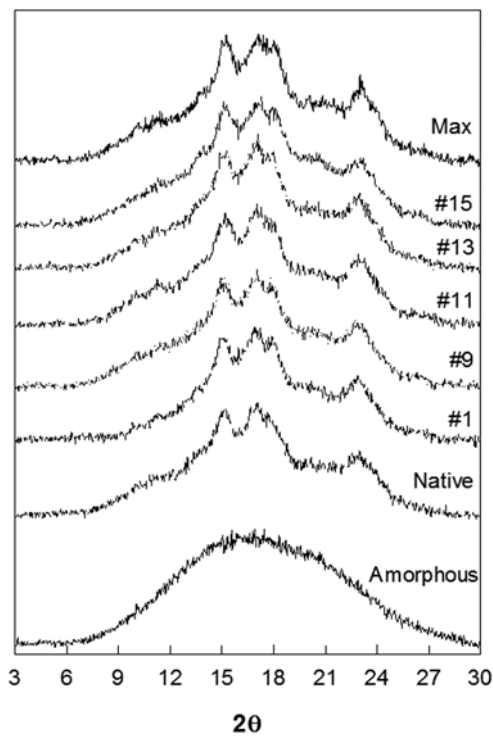
Fig. 2. X-ray diffraction patterns of native and heat-moisture treated sweetpotato flours.

sample 15. It indicated that intensities and crystallinities in the heat-moisture treated flour were influenced by the level of moisture content. Gunaratne and Hoover (6) reported that double helical movement during HMT could disrupt starch crystallites and change crystallite orientation. This would explain the observed changes in crystallinity and intensity following heat-moisture treatment. In conclusion, the result from the heat-moisture treated samples represented a significant negative correlation between relative crystallinity and treatment temperature and moisture level.

Gelatinization parameters   The gelatinization parameters (T_o, T_p, T_c, and ΔH) of native and heat-moisture treated

Table 4. Relative crystallinity of native and heat-moisture treated sweetpotato flours

Sample	Relative crystallinity (%)
Native	$33.8 \pm 1.6^{a1)}$
# 1 (23%, 130°C, 15 h)	29.7 ± 0.3^b
# 9 (28%, 110°C, 1 h)	27.8 ± 0.5^d
# 11 (23%, 90°C, 15 h)	29.4 ± 0.1^{bc}
# 13 (18%, 130°C, 8 h)	28.2 ± 0.7^{cd}
# 15 (28%, 130°C, 8 h)	25.7 ± 0.2^e
# Max (22%, 103°C, 5.8 h)	33.1 ± 0.6^a

[1]Values with different superscripts within a column are significantly different ($p<0.05$) by Duncan's multiple range test.

sweetpotato flour are presented in Table 5. The HMT samples showed increases in T_o, T_p, and T_c, and a decrease in gelatinization enthalpies (ΔH) in comparsion to the corresponding native sample. There was a shift in the endotherms to higher temperature regions in most of the treated samples. The onset, peak, and conclusion gelatinization temperatures generally rise as the levels of heat and moisture increase. This increase has been well known for potato, cassava, true yam (6), corn (16,22), etc.

It has been reported that ΔH is due to the melting of imperfect amylopectin-based crystals, with potential contributions from crystal-packing and helix-melting enthalpies (23). Thus, the large decline in ΔH in samples 1 and 15 with treated temperature of 130°C indicated the disruption of double helices in the crystalline region by these treatments. Furthermore, the higher T_p and lower enthalpy of sample 1 and 15 compared with the native sample suggested that most of the semi-crystalline structure was destroyed and little concentrated crystalline region remained within the starch structure after HMT. The ΔH of sample 11 with moisture level of 23% showed a similar results with the native sample. It suggested that double helices were not disrupted under these treatment conditions (22). The process of gelatinization, which involves the melting of the crystalline regions and double helices, is

Table 5. Gelatinization parameters of native and heat-moisture treated sweetpotato flours

Sample	Transition temperature (°C)			T_c–T_o (°C)	ΔH (J/g)
	T_o[1]	T_p	T_c		
Native	$61.6 \pm 0.9^{d2)}$	70.6 ± 0.1^e	80.3 ± 0.2^e	18.7 ± 1.0^a	15.7 ± 0.9^a
# 1 (23%, 130°C, 15 h)	71.4 ± 0.7^{bc}	78.2 ± 0.6^b	88.1 ± 1.0^b	16.6 ± 0.4^b	10.6 ± 1.1^d
# 9 (28%, 110°C, 1 h)	72.8 ± 0.1^a	78.5 ± 0.2^b	87.4 ± 0.0^b	14.7 ± 0.1^c	11.1 ± 0.1^d
# 11 (23%, 90°C, 15 h)	71.6 ± 0.3^c	76.5 ± 0.0^d	83.3 ± 0.2^d	11.7 ± 0.2^e	14.5 ± 0.4^{ab}
# 13 (18%, 130°C, 8 h)	71.4 ± 0.5^{bc}	77.6 ± 0.1^c	86.1 ± 0.1^c	14.7 ± 0.6^c	12.0 ± 0.3^{cd}
# 15 (28%, 130°C, 8 h)	72.4 ± 0.1^a	79.2 ± 0.0^a	90.4 ± 0.2^a	18.0 ± 0.2^a	7.7 ± 1.4^e
# Max (22%, 103°C, 5.8 h)	70.7 ± 0.3^c	76.7 ± 0.0^d	83.5 ± 0.2^d	12.8 ± 0.1^d	13.0 ± 1.2^{bc}

[1]T_o, T_p, T_c, T_c-T_o, and ΔH indicate the onset, peak, and conclusion temperatures, the temperature range of gelatinization, gelatinization enthalpy, respectively.
[2]Values with different superscripts within a column are significantly different ($p<0.05$) by Duncan's multiple range test.
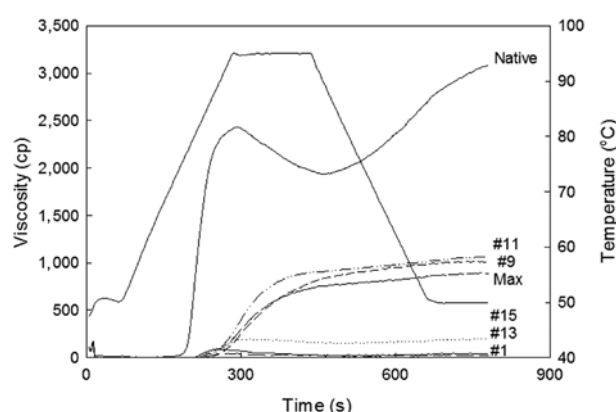
Fig. 3. RVA pasting profiles of native and heat-moisture treated sweetpotato flours.

determined by the hydration and swelling of the amorphous regions of starch granules (24). When the amorphous region swells, it conveys a stress on the crystalline regions and polymer chains are stripped from the surface of starch crystallites. After HMT, the amylose-amylose and amylose-lipid interactions reduce the mobility of the amorphous region. In sum, heat-moisture treated flour required a higher temperature in order for swelling and disruption of the crystalline regions to occur, leading to increased T_o, T_p, and T_c (25).

Pasting properties The rapid visco analyser (RVA) pasting profiles of native and heat-moisture treated flours are presented in Fig. 3 and the swelling factor in Table 6. Pasting temperature of heat-moisture treated flour was higher than that of native flour. In this study, when sweetpotato flour was heat-moisture treated, the peak viscosity and final viscosity decreased. Flour and starch pasting properties were considerably influenced by HMT condition and they were varied in accordance with different HMT conditions. The general effects of HMT on pasting properties were lower peak viscosities, no breakdown, and noticeable decreases in setback values for sweetpotato flours.

As the forces of the intragranular bonds are strengthened,

the starch requires more heat for structural disintegration and paste formation. A high paste temperature thus indicates that more forces and cross-links are present within the starch granules (26). The temperature had a considerable influence on viscosity value. Sample 1, 13, and 15 were treated at a higher temperature (130ºC) than the others. There was not much difference between peak viscosity and final viscosity. In that case, breakdown and setback became slightly different. The breakdown is regarded as the measure the degree of disintegration of granules or paste stability (27). The setback reveals the gelling ability or retrogradation tendency of amylose. There was a considerable decrease in viscosity breakdown and setback viscosity for sweetpotato flour after HMT, which indicates better paste stability (8).

Swelling factor and color values The swelling factors of various heat-moisture treated flours are presented in Table 6. It has been reported that the swelling volumes of all the starches are reduced after HMT (8). The swelling factors of sample 1, 9, 13, 15, and Max were lower than that of the native sample. Especially, the sample 1, 13, and 15, which were reacted at 130ºC, showed a large decrease in swelling factor compared with native and the other samples. Jyothi *et al*. (8) suggested that higher levels of temperature of HMT bring about a decrease in swelling volume of the starch.

This result could be attributed to interplay of 2 factors. The first one is that swelling starts in the relatively mobile amorphous fraction and in the more controlled amorphous regions immediately contiguous to the crystalline regions (22). Therefore, the decrease in swelling factor was caused by the interaction between or among starch components in amorphous regions of the granule (28). This reduction in swelling power has also been attributed to increased crystallinity, reduced hydration (29), increased interactions between amylose and amylopectin molecules, strengthened intermolecular bonds, the formation of amylose-lipid complexes and changes in the arrangements of the crystalline regions of starch (30).

The changes in color values of sweetpotato flour caused by HMT are shown in Table 6. The surface color of

Table 6. Swelling factor and Hunter color values of native and heat-moisture treated sweetpotato flours

Sample	Swelling factor	L	a	b	ΔE
Native	23.9±0.0[a1)]	92.4[a]	0.17[b]	6.3[d]	7.9[g]
# 1 (23%, 130ºC, 15 h)	5.2±1.0[de]	85.6[e]	0.30[a]	13.4[a]	46.3[a]
# 9 (28%, 110ºC, 1 h)	6.7±0.5[d]	89.1[b]	-0.49[e]	6.9[c]	9.6[f]
# 11 (23%, 90ºC, 15 h)	21.6±0.1[b]	88.7[bc]	-0.39[d]	7.1[c]	10.0[e]
# 13 (18%, 130ºC, 8 h)	5.0±0.7[e]	86.2[de]	0.19[b]	11.7[b]	14.7[b]
# 15 (28%, 130ºC, 8 h)	5.6±1.3[de]	86.6[d]	0.08[c]	11.7[b]	14.5[c]
Max (22%, 103ºC, 5.8 h)	10.3±1.8[c]	88.2[c]	0.12[c]	6.3[d]	12.6[d]

[1)]Values with different superscripts within a column are significantly different (*p*<0.05) by Duncan's multiple range test.

sweetpotato flour was most affected by treatment temperature. The samples treated at 130°C, such as sample 1, 13, and 15 were in low L values. Judging from a negative correlation between brightness and treatment temperature, brighter color of sweetpotato flour indicated more SDS and RS contents. Therefore, it could be useful in developing food products where sweetpotato flour is simply added or used as a main ingredient.

In conclusion, sweetpotato flour had a high content of SDS and RS. HMT caused disruption of crystallinity, dissociation of double helical structure, formation of hollow region in the granule, and no change in X-ray pattern (A type). These characteristics resulted in an increase of enzyme susceptibility. In addition, HMT influenced viscosity profile, reducing viscosity and increasing pasting temperature. The content of SDS in sweetpotato flour was most affected by temperature and reached 57.6% under optimum conditions. Overall, slowly digestible sweetpotato flour consisted of much amorphous regions and partially disrupted crystalline regions. The results of the present study suggest that heat-moisture treated sweetpotato flour could be tested as a potential candidate for processed foods with slow digestion properties.

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