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Resistant and Digestible Starch Contents in Sweet Potato Cultivars and Lines

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Abstract: The sweet potato is recognized as a health-promoting food, owing to its richness in functional components such as dietary fiber; however, only a few studies have been conducted on resistant starch (RS) levels in the sweet potato. Now, the sweet potato is expected to have potential as a renewable resource for bio-ethanol production. The enzymatic digestibility of raw starch appears to influence the conversion rate of starch to sugar in the first step of ethanol production. In this study, the RS content of gelatinized starch, digestible starch (DS) content of raw starch and other starch properties were investigated using 21 sweet potato cultivars and lines to assess varietal variations and to estimate relationships among these starch properties. The RS content of gelatinized starch ranged between 1.8 and 9.5%. The DS content of raw starch ranged between 69.3 and 98.3%. Analysis of variance indicated that the varietal differences were significant at the 0.1% level for both the RS content and the DS content. Sweet potato starches with high amylose content and low paste viscosity showed high RS content of gelatinized starch. Starches with low pasting temperature and slow retrogradation showed high DS content of raw starch. A new breeding line, Kyukei 03284-156, contained a unique starch having the highest RS content, highest amylose content, lowest paste viscosity and abnormal granule morphology. The results of this study are expected to provide useful information to food industries that utilize sweet potato starch and to breeders that attempt to improve the RS and DS contents in sweet potato cultivars.

Key words: amylose content, digestibility, resistant starch, sweet potato, varietal variation

The sweet potato (*Ipomoea batatas* L.) is one of the most important starch-producing crops in the tropics and warm-temperate regions of the world¹⁾ and is recognized as a health-promoting food, owing to its richness in functional components such as dietary fiber, vitamins, carotenes and anthocyanins.²⁾ The starch comprises a large digestible portion (digestible starch, DS) and a small nondigestible portion (enzymatic resistant starch, RS). RS is defined as the sum of starch and starch degradation products not absorbed in the small intestine of healthy individuals.^{3, 4)} RS that reaches the large intestine acts a substrate for microbial fermentation and finally produces short chain fatty acids (SCFAs), including butyrate, acetate and propionate. These SCFAs may play an important role in the prevention of bowel health disorders. Consumption of RS is considered to provide several health benefits to the human bowel and metabolism.³⁻⁵⁾ It is recognized that the sweet potato root contains high dietary fiber; however, only a few studies have been conducted on RS levels in the sweet potato.^{6, 7)}

The sweet potato has been a favorable raw material for alcohol fermentation and the production of sugar syrup and glucose in East Asia. Recently, research has focused on the potential of the sweet potato as a renewable resource for bio-

ethanol production.⁸⁾ The enzymatic digestibility of raw starch appears to influence the conversion rate of starch to sugar in the first step of ethanol production.⁹⁾ During the last decade, new sweet potato cultivars and lines with new starch properties, e.g., Quick Sweet, which has a low gelatinization temperature, have been developed in Japan.¹⁰⁻¹²⁾ However, only a few studies have been conducted on the digestibility of raw starch in these recently developed sweet potato cultivars and lines. Noda *et al.*⁹⁾ reported that the digestibility of raw starch by glucoamylase was negatively correlated with the average granule size in eight cultivars and lines. We reported that the digestibility of raw starch by pancreatin increased as gelatinization temperatures decreased in five cultivars and lines, including Quick Sweet.¹³⁾

In this study, the RS content of gelatinized starch, the DS content of raw starch and other starch properties were investigated using 21 sweet potato cultivars and lines to assess varietal variations and to estimate relationships among the RS content, the DS content and other starch properties. Furthermore, we found a unique sweet potato variant having high RS content, high amylose content, low paste viscosity and abnormal starch granule morphology.

MATERIALS AND METHODS

Twenty-one sweet potato cultivars and breeding lines

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were used (Table 1). Materials varying widely in starch properties were chosen to estimate the RS and DS contents. Koganesengan is a leading Japanese variety for *Shochu* (spirit) production. Shiroyutaka is a leading Japanese variety for starch production. Konahomare is a cultivar possessing high starch content for starch production. Kokei 14 and Beniazuma are leading Japanese varieties for table use. Tamayutaka is a leading Japanese variety for production of *Hoshi-imo* (steamed and dried sweet potato, a Japanese traditional sweet). Purple Sweet Lord and Tanegashimamurasaki are cultivars possessing high anthocyanin content for table use and processing foods. Ayakomachi and Sunny Red are cultivars rich in carotene content for table use and processing foods. Tokyokintoki is a cultivar with a high amylose content for table use. Kyukei 00212-17 and Kyukei 89376-12 are breeding lines having a low amylose content. Kyukei 98144-9 and Kyukei 98104-6 are breeding lines having a rapid retrogradation. Quick Sweet is a cultivar characterized by a low pasting temperature for table use. Kyushu 127 is a breeding line having a moderately low pasting temperature. Kyushu 159 and 99L03-1 are breeding lines having a low pasting temperature. 99L04-13 is a breeding line having low pasting temperature and high amylose content. Kyukei 03284-156 is a breeding line having high amylose content and low paste viscosity.

All plant materials were grown with two replications in the experiment field of the National Agricultural Research Center for Kyushu Okinawa Region in Miyakonojo, Japan. Materials were transplanted in late May and harvested in mid-October 2006. Harvested storage roots were stored at 15°C and 80% relative humidity for at least two weeks. Four to eight medium-sized storage roots per plot were then randomly selected for starch extraction. Starch extraction from storage roots was conducted according to a previously re-

ported method.¹¹⁾ The starches of potato and maize (Wako Pure Chemical Industries Ltd., Osaka, Japan) were also used to compare the RS and DS contents.

RS and DS contents were determined enzymatically according to AOAC International official method 2002.02 and AACC method 32-40¹⁴⁾ with resistant starch assay procedure RSTAR 11/02 (Megazyme International Ireland Ltd., Wicklow, Ireland). The DS content was calculated from the difference between the total starch content and the RS content. The RS content was determined in gelatinized starch, and the DS content was estimated in raw starch granules. First, 10% aqueous starch suspensions were gelatinized by stirring in a water bath at 100°C for 20 min. Next, starch pastes were frozen at -35°C for one night and subsequently freeze-dried. The freeze-dried starch pastes were milled and used as gelatinized starch samples.

Amylose content was determined at a wavelength of 680 nm.¹⁵⁾ Starch pasting properties were investigated using a Rapid Visco-Analyzer (RVA Super 3, Newport Scientific Pty. Ltd., Warriewood, Australia) with 7% starch suspension.¹²⁾ Starch retrogradation was evaluated by the percentage of leaked water and hardness of 8% starch gel after cold storage for two hours and six weeks at 5°C.¹⁶⁾ The hardness was measured using a digital force gauge (FGC-2, SHIMPO Ltd., Kyoto, Japan) with a plunger whose diameter was 6 mm. The depth to which the plunger pierced through the gel was 1 cm. Starch granules were suspended in water and viewed with a light microscope, or were sputter-coated with gold and viewed with a scanning electron microscope (JSM-5300LV, JEOL Ltd., Tokyo, Japan). Starch granule size was measured using a digital sight camera control unit (DS-L1, Nikon Instruments Inc., New York, USA) attached to a light microscope. Average granule size was calculated from 1,200 granules per plot. Starch content (fresh-weight basis) was determined by the sedimentation method after blending 200 g of root tissues in 500 mL of water.¹⁵⁾

We prepared a mixture of two starch extractions per plot and two plots per cultivar or line. All analyses were performed in duplicate. Each value was the mean $\pm$ SD of two plots. The analysis of variance (ANOVA) was carried out on the basis of the data of the two plots. The correlation coefficients among the starch properties were calculated in 21 cultivars and lines.

RESULTS

Table 1 lists the mean values $\pm$ SD of the RS content of gelatinized starch and DS content of raw starch in 21 sweet potato cultivars and lines. The RS content of gelatinized starch ranged from 1.8% for 99L03-1 to 9.5% for Kyukei 03284-156. The RS content of gelatinized starch in potato and maize was 3.5 and 5.2%, respectively. The mean of RS contents of sweet potato was similar to that of potato, and the highest RS content of sweet potato was higher than that of maize. The DS content of raw starch ranged from 69.3% for Kyukei 98104-6 to 98.3% for Quick Sweet. The DS content of raw starch in potato and maize was 20.8 and 99.3%, respectively. The DS contents of sweet potato were higher than that of potato, and the highest DS content of sweet potato was similar to that of maize.

Table 2 lists the mean values $\pm$ SD of amylose content and

Table 1. RS and DS contents in 21 sweet potato cultivars and lines.

Cultivar or line	RS content of gelatinized starch (%)	DS content of raw starch (%)
Koganesengan	4.2 $\pm$ 0.0	79.7 $\pm$ 1.3
Shiroyutaka	4.1 $\pm$ 0.2	75.8 $\pm$ 1.1
Kokei 14	4.2 $\pm$ 0.2	88.4 $\pm$ 0.5
Beniazuma	4.1 $\pm$ 0.0	77.2 $\pm$ 0.4
Tamayutaka	2.7 $\pm$ 0.1	81.1 $\pm$ 1.0
Purple Sweet Lord	4.4 $\pm$ 0.1	70.6 $\pm$ 2.2
Tanegashimamurasaki	2.5 $\pm$ 0.0	81.1 $\pm$ 1.9
Ayakomachi	3.9 $\pm$ 0.1	86.4 $\pm$ 0.1
Sunny Red	4.6 $\pm$ 0.3	84.5 $\pm$ 1.3
Konahomare	4.3 $\pm$ 0.1	72.5 $\pm$ 1.0
Tokyokintoki	3.5 $\pm$ 0.1	79.9 $\pm$ 0.2
Kyukei 00212-17	3.4 $\pm$ 0.1	82.5 $\pm$ 0.5
Kyukei 89376-12	3.7 $\pm$ 0.1	80.3 $\pm$ 0.1
Kyukei 98144-9	2.8 $\pm$ 0.3	73.1 $\pm$ 2.6
Kyukei 98104-6	4.4 $\pm$ 0.3	69.3 $\pm$ 0.2
Kyushu 127	2.5 $\pm$ 0.1	97.7 $\pm$ 0.2
Kyushu 159	2.5 $\pm$ 0.1	96.6 $\pm$ 1.1
Quick Sweet	2.9 $\pm$ 0.1	98.3 $\pm$ 0.2
99L03-1	1.8 $\pm$ 0.1	87.4 $\pm$ 0.4
99L04-13	5.8 $\pm$ 0.1	97.7 $\pm$ 0.0
Kyukei 03284-156	9.5 $\pm$ 0.7	96.0 $\pm$ 0.5
Mean $\pm$ SD	3.9 $\pm$ 1.5	83.6 $\pm$ 9.1
Potato	3.5	20.8
Maize	5.2	99.3

pasting properties in the 21 sweet potato cultivars and lines. Amylose content (percentage of starch) ranged from 12.3% for Kyukei 00212-17 to 25.3% for Kyukei 03284-156. Pasting temperature ranged from 57.1°C for Quick Sweet to 80.3°C for Kyukei 03284-156. Peak viscosity ranged from 52 Rapid Visco-Analyzer Units (RVU) for Kyukei 03284-156 to 301 RVU for 99L03-1. The breakdown value ranged from 0 RVU for Kyukei 03284-156 to 175 RVU for 99L03-1. The setback value ranged from 81 RVU for Kyukei 03284-156 to 227 RVU for 99L04-13. These values of the amylose content and pasting properties were similar to those reported

in previous studies.^{10–13, 15)} Kyukei 03284-156 contained a unique starch having the highest amylose content and lowest paste viscosity.

Table 3 lists the mean values $\pm$ SD of retrogradation, average granule size, and starch content in the 21 sweet potato cultivars and lines. The percentage of leaked water of starch gel ranged from 0.0% for Kyushu 159, Quick Sweet and 99L03-1 to 25.9% for Kyukei 98144-9. The gel hardness after 2 h ranged from 0.25 N for Kyukei 00212-17 to 0.92 N for 99L04-13. The gel hardness after six weeks ranged from 0.49 N for Kyushu 159 to 2.24 N for Kyukei 98144-9. The

Table 2. Amylose content and pasting properties in 21 sweet potato cultivars and lines.

Cultivar or line	Amylose content (%)	Pasting temperature (°C)	Peak viscosity (RVU)	Break-down (RVU)	Setback (RVU)
Koganesengan	17.5 $\pm$ 0.1	75.4 $\pm$ 0.3	217 $\pm$ 3	102 $\pm$ 3	135 $\pm$ 0
Shiroyutaka	18.8 $\pm$ 0.3	75.8 $\pm$ 0.0	259 $\pm$ 9	133 $\pm$ 7	143 $\pm$ 4
Kokei 14	17.3 $\pm$ 0.1	74.6 $\pm$ 0.6	256 $\pm$ 3	138 $\pm$ 2	145 $\pm$ 1
Beniazuma	16.2 $\pm$ 0.0	75.7 $\pm$ 0.5	248 $\pm$ 11	138 $\pm$ 13	135 $\pm$ 2
Tamayutaka	17.4 $\pm$ 0.1	72.3 $\pm$ 0.7	258 $\pm$ 9	118 $\pm$ 4	143 $\pm$ 1
Purple Sweet Lord	14.6 $\pm$ 0.1	78.6 $\pm$ 0.8	228 $\pm$ 4	119 $\pm$ 4	113 $\pm$ 6
Tanegashimamurasaki	15.3 $\pm$ 0.2	71.6 $\pm$ 0.8	251 $\pm$ 5	111 $\pm$ 1	152 $\pm$ 6
Ayakomachi	18.6 $\pm$ 0.1	73.5 $\pm$ 0.3	262 $\pm$ 0	144 $\pm$ 2	151 $\pm$ 4
Sunny Red	18.7 $\pm$ 0.1	74.5 $\pm$ 1.1	236 $\pm$ 7	121 $\pm$ 7	147 $\pm$ 1
Konahomare	18.3 $\pm$ 0.3	77.2 $\pm$ 0.1	240 $\pm$ 8	120 $\pm$ 5	144 $\pm$ 2
Tokyokintoki	19.4 $\pm$ 0.1	73.6 $\pm$ 0.4	227 $\pm$ 12	97 $\pm$ 10	158 $\pm$ 2
Kyukei 00212-17	12.3 $\pm$ 0.2	75.8 $\pm$ 0.2	240 $\pm$ 9	122 $\pm$ 3	118 $\pm$ 10
Kyukei 89376-12	12.6 $\pm$ 0.0	77.0 $\pm$ 0.5	252 $\pm$ 10	138 $\pm$ 11	122 $\pm$ 4
Kyukei 98144-9	17.9 $\pm$ 0.0	74.2 $\pm$ 0.2	256 $\pm$ 3	89 $\pm$ 12	182 $\pm$ 10
Kyukei 98104-6	18.0 $\pm$ 0.1	78.1 $\pm$ 0.0	265 $\pm$ 6	120 $\pm$ 4	143 $\pm$ 3
Kyushu 127	16.7 $\pm$ 0.1	66.7 $\pm$ 0.3	228 $\pm$ 21	99 $\pm$ 17	156 $\pm$ 1
Kyushu 159	17.4 $\pm$ 0.1	58.8 $\pm$ 0.5	246 $\pm$ 3	114 $\pm$ 4	152 $\pm$ 5
Quick Sweet	16.5 $\pm$ 0.2	57.1 $\pm$ 0.8	203 $\pm$ 14	62 $\pm$ 9	147 $\pm$ 2
99L03-1	16.7 $\pm$ 0.2	60.8 $\pm$ 0.1	301 $\pm$ 15	175 $\pm$ 6	164 $\pm$ 12
99L04-13	21.4 $\pm$ 0.6	60.5 $\pm$ 1.0	126 $\pm$ 6	4 $\pm$ 1	227 $\pm$ 13
Kyukei 03284-156	25.3 $\pm$ 1.5	80.3 $\pm$ 1.6	52 $\pm$ 3	0 $\pm$ 0	81 $\pm$ 1
Mean $\pm$ SD	17.5 $\pm$ 2.7	72.0 $\pm$ 6.8	231 $\pm$ 51	108 $\pm$ 41	145 $\pm$ 27

Table 3. Retrogradation, average granule size and starch content in 21 sweet potato cultivars and lines.

Cultivar or line	Leaked water (%)	Hardness after 2 h (N)	Hardness after 6 weeks (N)	Average granule size (μ m)	Starch content (%)
Koganesengan	19.4 $\pm$ 0.3	0.43 $\pm$ 0.03	1.78 $\pm$ 0.01	11.1 $\pm$ 0.5	20.9 $\pm$ 1.1
Shiroyutaka	21.5 $\pm$ 0.4	0.51 $\pm$ 0.02	1.94 $\pm$ 0.14	10.2 $\pm$ 0.2	24.1 $\pm$ 0.1
Kokei 14	20.3 $\pm$ 0.8	0.43 $\pm$ 0.01	1.92 $\pm$ 0.01	10.6 $\pm$ 1.2	19.7 $\pm$ 0.7
Beniazuma	18.2 $\pm$ 0.0	0.39 $\pm$ 0.03	1.82 $\pm$ 0.15	10.7 $\pm$ 1.4	23.3 $\pm$ 0.1
Tamayutaka	21.5 $\pm$ 0.6	0.44 $\pm$ 0.02	1.92 $\pm$ 0.11	11.3 $\pm$ 0.7	20.4 $\pm$ 1.0
Purple Sweet Lord	19.0 $\pm$ 0.9	0.36 $\pm$ 0.09	1.58 $\pm$ 0.21	9.9 $\pm$ 0.2	20.8 $\pm$ 0.3
Tanegashimamurasaki	17.1 $\pm$ 2.4	0.33 $\pm$ 0.03	1.21 $\pm$ 0.16	12.0 $\pm$ 0.2	19.9 $\pm$ 0.1
Ayakomachi	19.2 $\pm$ 0.2	0.44 $\pm$ 0.03	1.72 $\pm$ 0.06	10.8 $\pm$ 0.3	16.3 $\pm$ 0.4
Sunny Red	19.8 $\pm$ 0.6	0.46 $\pm$ 0.06	1.89 $\pm$ 0.10	8.0 $\pm$ 0.8	19.8 $\pm$ 0.0
Konahomare	20.5 $\pm$ 0.0	0.43 $\pm$ 0.01	1.95 $\pm$ 0.02	9.1 $\pm$ 1.0	26.2 $\pm$ 1.6
Tokyokintoki	21.1 $\pm$ 0.5	0.55 $\pm$ 0.04	1.82 $\pm$ 0.03	12.3 $\pm$ 0.4	23.3 $\pm$ 1.1
Kyukei 00212-17	14.9 $\pm$ 0.5	0.25 $\pm$ 0.02	0.79 $\pm$ 0.02	11.8 $\pm$ 0.0	17.1 $\pm$ 0.7
Kyukei 89376-12	13.8 $\pm$ 0.0	0.27 $\pm$ 0.01	0.99 $\pm$ 0.02	11.5 $\pm$ 0.2	17.0 $\pm$ 0.1
Kyukei 98144-9	25.9 $\pm$ 1.2	0.57 $\pm$ 0.07	2.24 $\pm$ 0.07	10.4 $\pm$ 1.3	17.0 $\pm$ 2.4
Kyukei 98104-6	23.2 $\pm$ 0.3	0.58 $\pm$ 0.04	2.22 $\pm$ 0.13	9.9 $\pm$ 0.1	25.8 $\pm$ 0.3
Kyushu 127	3.4 $\pm$ 0.1	0.43 $\pm$ 0.00	0.80 $\pm$ 0.00	12.0 $\pm$ 1.4	20.0 $\pm$ 0.7
Kyushu 159	0.0 $\pm$ 0.0	0.45 $\pm$ 0.04	0.49 $\pm$ 0.03	15.5 $\pm$ 0.4	23.5 $\pm$ 0.6
Quick Sweet	0.0 $\pm$ 0.0	0.61 $\pm$ 0.05	0.55 $\pm$ 0.07	12.8 $\pm$ 0.7	21.4 $\pm$ 1.9
99L03-1	0.0 $\pm$ 0.0	0.31 $\pm$ 0.01	0.50 $\pm$ 0.04	16.4 $\pm$ 0.4	23.0 $\pm$ 1.0
99L04-13	3.5 $\pm$ 1.1	0.92 $\pm$ 0.01	0.85 $\pm$ 0.02	11.6 $\pm$ 0.3	17.7 $\pm$ 0.7
Kyukei 03284-156	7.1 $\pm$ 0.9	0.91 $\pm$ 0.05	0.84 $\pm$ 0.13	9.0 $\pm$ 0.4	10.4 $\pm$ 3.2
Mean $\pm$ SD	14.7 $\pm$ 8.3	0.48 $\pm$ 0.17	1.42 $\pm$ 0.59	11.3 $\pm$ 1.9	20.3 $\pm$ 3.6

average granule size ranged from 8.0 μm for Sunny Red to 16.4 μm for 99L03-1. Starch content (fresh-weight basis) ranged from 10.4% for Kyukei 03284-156 to 26.2% for Konahomare. These values of the retrogradation, average granule size, and starch content were similar to those reported in previous studies.^{9, 12, 15, 16} Starches with low pasting temperatures exhibited slower retrogradation and larger granule size than the ordinary starches. ANOVA on the data of the two replications indicated that the varietal differences were significant at the 0.1% level for all analyzed characteristics, including the RS content and DS content.

Figure 1 shows light and scanning electron micrographs

of starch granules from three cultivars and lines. Fifteen cultivars and lines (including Koganesengan) having ordinary pasting temperatures contained granules typical of sweet potato starch in appearance (Figs. 1-1A and 1B). Starch granules of five cultivars and lines (including Kyushu 159) having low pasting temperatures were cracked in the center under the light microscope (Fig. 1-2A). Starch granules of Kyukei 03284-156 were extremely distorted and cracked under the light microscope (Fig. 1-3A). Under the scanning electron microscope, some of these starch granules had big cracks and holes on the surface (Fig. 1-3B). These results of starch granule morphology were similar to those reported in

Fig. 1. Light (A) and scanning electron (B) micrographs of starch granules from Koganesengan (1), Kyushu 159 (2) and Kyukei 03284-156 (3). The bars in the light micrographs indicate 20 μm .

Table 4. Correlation coefficients between RS content, DS content, amylose content, pasting properties, retrogradation, granule size and starch content.

	RS content	DS content	Amylose content	Pasting temperature	Peak viscosity	Break-down	Setback	Leaked water	Hardness after 2 h	Hardness after 6 weeks	Average granule size
DS content	0.122	—	—	—	—	—	—	—	—	—	—
Amylose content	0.686**	0.311	—	—	—	—	—	—	—	—	—
Pasting temperature	0.438*	-0.691**	0.006	—	—	—	—	—	—	—	—
Peak viscosity	-0.833**	-0.483*	-0.667**	-0.022	—	—	—	—	—	—	—
Breakdown	-0.638**	-0.477*	-0.636**	0.156	0.922**	—	—	—	—	—	—
Setback	-0.368	0.185	0.118	-0.591**	0.156	-0.122	—	—	—	—	—
Leaked water	0.034	-0.832**	-0.087	0.789**	0.336	0.323	-0.141	—	—	—	—
Hardness after 2 h	0.714**	0.446*	0.871**	-0.135	-0.833**	-0.872**	0.203	-0.270	—	—	—
Hardness after 6 weeks	0.059	-0.752**	0.109	0.657**	0.310	0.267	0.014	0.934**	-0.118	—	—
Average granule size	-0.601**	0.415	-0.283	-0.758**	0.297	0.216	0.297	-0.653**	-0.213	-0.655**	—
Starch content	-0.510*	-0.398	-0.248	-0.165	0.594**	0.497*	0.228	0.139	-0.378	0.277	0.218

*,** Significant at 5 and 1%, respectively.

previous studies.^{11, 12)} Kyukei 03284-156 is a unique sweet potato variant having abnormal starch granule morphology.

Table 4 lists the correlation coefficients between the RS content, DS content, amylose content, pasting properties, retrogradation, average granule size and starch content. The RS content of gelatinized starch was positively correlated with the amylose content and hardness after 2 h, and negatively correlated with the peak viscosity, breakdown, and average granule size, tested at a 1% significance level. The RS content exhibited negative correlation with the starch content tested at a 5% significance level. These results indicate that sweet potato starches with higher amylose content, lower paste viscosity, and smaller granule size show higher RS content of gelatinized starch. In addition, plant breeders need to take into account the total starch content in roots when attempting to improve the RS content in the sweet potato.

The DS content of raw starch was negatively correlated with the pasting temperature, leaked water percentage, and hardness after six weeks tested at a 1% significance level. The DS content did not exhibit a significant correlation with the amylose content, average granule size, or starch content. These results indicate that sweet potato starches with lower pasting temperature and slower retrogradation show higher DS content of raw starch and that it is possible to alter the digestibility of raw starch, regardless of the starch content and amylose content.

The amylose content was positively correlated with the hardness after 2 h, and negatively correlated with the peak viscosity and breakdown, tested at a 1% significance level. The pasting temperature was positively correlated with the leaked water percentage and hardness after six weeks tested at a 1% significance level. The average granule size was negatively correlated with the pasting temperature, leaked water percentage and hardness after six weeks. These results indicate that the amylose content has an influence on the retrogradation of sweet potato starch during the early stage of the retrogradation progress, which is similar to the results of a previous study;¹⁶⁾ further, the starches with a low pasting temperature show slow retrogradation similar to that reported in previous studies.^{12, 13)} In addition, these results suggest that sweet potato starches with high amylose content show low paste viscosity and that starches with a low pasting temperature and slow retrogradation show a large granule size.

DISCUSSION

Only a few studies have been conducted on the levels of RS in the sweet potato.^{6, 7)} Furthermore, few studies have examined the varietal variations in the RS content of the sweet potato. In this study, we found that the varietal differences in the RS content of the sweet potato were significant at the 0.1% level.

RS is subdivided into 4 fractions: RS1, RS2, RS3 and RS4.^{3, 4)} RS1 is the physically inaccessible starch in substances such as whole grains and very dense types of processed foods. RS2 is the ungelatinized resistant granule with type B crystallinity. RS3 is the retrograded starch formed during the cooling of gelatinized starch. Finally, RS4 is the starch chemically modified by cross-linking with chemical reagents. The RS of gelatinized starch in this study is analogous to RS3. RS contents of raw starch calculated from Table 1 ranged from 1.7 to 30.7%, and this RS of raw starch corresponds to RS2. In most of the sweet potato cultivars and lines, the RS contents of gelatinized starch were lower than those of raw starch. These results indicate that cooked (gelatinized) starch shows higher digestibility than raw starch in most of the sweet potato cultivars and lines. However, the RS contents of gelatinized starch were clearly higher than those of raw starch in Quick Sweet, 99L04-13 and Kyukei 03284-156. We speculate that the particular starch structures of these lines may form the RS3-like aggregates during gelatinization and subsequent freeze-drying treatment. Thus, further investigation about the crystalline and molecular structure of raw starch and RS is necessary for elucidating the mechanism of increasing RS of gelatinized starch in these lines.

During the last two decades, many studies on other crops reported that the RS content was influenced by the amylose content and increased as amylose content increased.^{4, 17–20)} Novel cultivars and mutants having high amylose and RS contents were developed.^{21, 22)} Previous studies using rice^{18, 22)} reported that starches with high RS content were characterized by high amylose content and low paste viscosity. The results of our study on the sweet potato were similar to those of previous studies on other crops. Recently, we developed a new sweet potato breeding line, Kyukei 03284-156. This new line contains a unique starch with high amylose content, high RS content, low paste viscosity and abnormal granule morphology. This line is expected to be a valuable material

for improving the RS content in the sweet potato and estimating the physiological effects of sweet potato RS.

According to Fuwa *et al.*,²³⁾ the relative order of digestibility of various plant starches by amylase was rice > maize > sweet potato > potato. We reported that Quick Sweet starch granules having a low gelatinization temperature were digested rapidly by pancreatin.¹³⁾ In this study, sweet potato cultivars and lines having low pasting temperature and slow retrogradation exhibited high DS content of raw starch, similar to that of maize. These results indicate that selecting lines with low pasting temperatures is an effective way to develop new sweet potato cultivars having high digestibility of raw starch. It has been reported that the starch granule size is an important factor in affecting the digestibility of raw starch and that larger granule size results in lower digestibility of raw starch in tuber and root crops.^{24,25)} However, in this study, the DS content did not exhibit a significant correlation with the average granule size and the sweet potato starches with a low pasting temperature, slow retrogradation and large granule size showed high DS content. Previous studies^{11, 13, 26)} reported that sweet potato starches with low pasting temperature have a high proportion of short chains (DP 6–10) in amylopectin and these starches have cracks within their granules, which may be caused by changes in the crystallinity of the granules. The high digestibility of raw starch having a low pasting temperature is due to these distinctive characteristics, and not the starch granule size. These sweet potato starches, which are distinct from the starches used in the studies of Noda *et al.*,^{9, 24, 25)} may be responsible for these different results. Further, the DS content did not significantly correlate with the starch content. This result suggests that it is possible to develop new sweet potato cultivars having both the high digestibility of raw starch and high starch content, which will be suitable as renewable resources for bioethanol production.

In Japan, most sweet potato starch is used to produce sugar syrup or glucose, with the remainder employed to produce foodstuffs such as starch noodles and gelatinized cakes. Sweet potato starches with low pasting temperature and slow retrogradation are expected to be suitable for foodstuffs such as gelatinized cakes and pastries.¹²⁾ Recently, some starch companies began to investigate an application area of sweet potato starches with a low pasting temperature. Further investigation about food processing use is necessary for developing new applications of sweet potato starches with a low pasting temperature.

A breeding line, Kyushu 159, having a low pasting temperature, slow retrogradation and high DS content was newly released as a new cultivar for starch production in 2010. Root yield, starch content and starch yield of Kyushu 159 are similar to those of Shiroyutaka, a leading Japanese variety for starch production. Kyushu 159 is expected to be used in foodstuffs such as gelatinized cakes. In addition, the production of bioethanol from sweet potato with a high digestibility of raw starch has an advantage in that the conversion of starch to sugar will be able to proceed without the starch gelatinization step. Kyushu 159 has the potential to be used as a renewable resource of bioethanol. The results of this study are expected to provide useful information to food industries that utilize sweet potato starch and to breeders attempting to improve the RS and DS contents in sweet potato

cultivars.

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REFERENCES

- 1) J.A. Wolfe: *Sweetpotato: an Untapped Food Resource*, Cambridge University Press, Cambridge, pp. 48–49 (1992).
- 2) G. Padmaja: Uses and nutritional data of sweetpotato. in *The Sweetpotato*, G. Loebenstein and G. Thottappilly, eds., Springer Science + Business Media, Dordrecht, pp. 189–234 (2009).
- 3) A.P. Nugent: Health properties of resistant starch. *Nutr. Bull.*, **30**, 27–54 (2005).
- 4) M.G. Sajilata, R.S. Singhal and P.R. Kulkarni: Resistant starch—a review. *Comprehensive Reviews in Food Science and Food Safety*, **5**, 1–17 (2006).
- 5) J.A. Higgins: Resistant starch: metabolic effects and potential health benefits. *J. AOAC Int.*, **87**, 761–768 (2004).
- 6) S.I. Shin, J. Byun, K.H. Park and T.W. Moon: Effect of partial acid hydrolysis and heat-moisture treatment on formation of resistant tuber starch. *Cereal Chem.*, **81**, 194–198 (2004).
- 7) I. Mahmood, P.S. Ghugre and S.A. Udipi: Resistant starch in raw and processed roots and tubers. *J. Food Sci. Technol.*, **43**, 282–285 (2006).
- 8) L.H. Ziska, G.B. Runion, M. Tomecek, S.A. Prior, H.A. Torbet and R. Sicher: An evaluation of cassava, sweet potato and field corn as potential carbohydrate sources for bioethanol production in Alabama and Maryland. *Biomass and Bioenergy*, **33**, 1503–1508 (2009).
- 9) T. Noda, Y. Takahata, T. Nagata and M. Monma: Digestibility of sweet potato raw starches by glucoamylase. *Starch/Stärke*, **44**, 32–35 (1992).
- 10) K. Kitahara, J. Ueno, T. Suganuma, K. Ishiguro and O. Yamakawa: Physicochemical properties of root starches from new types of sweetpotato. *J. Appl. Glycosci.*, **46**, 391–397 (1999).
- 11) K. Katayama, K. Komae, K. Kohyama, T. Kato, S. Tamiya and K. Komaki: New sweetpotato line having low gelatinization temperature and altered starch structure. *Starch/Stärke*, **54**, 51–57 (2002).
- 12) K. Katayama, S. Tamiya and K. Ishiguro: Starch properties of new sweet potato lines having low pasting temperature. *Starch/Stärke*, **56**, 563–569 (2004).
- 13) K. Kitahara, S. Fukunaga, K. Katayama, Y. Takahata, Y. Nakazawa, M. Yoshinaga and T. Suganuma: Physicochemical properties of sweetpotato starches with different gelatinization temperatures. *Starch/Stärke*, **57**, 473–479 (2005).
- 14) B.V. McCleary and D.A. Monaghan: Measurement of resistant starch. *J. AOAC Int.*, **85**, 665–675 (2002).
- 15) K. Katayama, K. Komaki, S. Tamiya and K. Takayanagi: Varietal and annual variations in pasting properties of sweet potato starch. *Breed. Sci.*, **49**, 173–178 (1999).
- 16) K. Ishiguro, T. Noda, K. Kitahara and O. Yamakawa: Retrogradation of sweetpotato starch. *Starch/Stärke*, **52**, 13–17 (2000).
- 17) M.K. Morell, C. Konik-Rose, R. Ahmed, Z. Li and S. Rahman: Synthesis of resistant starches in plants. *J. AOAC Int.*, **87**, 740–748 (2004).
- 18) P. Hu, H. Zhao, Z. Duan, Z. Linlin and D. Wu: Starch digestibility and the estimated glycemic score of different types of rice differing in amylose contents. *J. Cereal Sci.*, **40**, 231–237 (2004).
- 19) A.M. Leeman, M.E. Karlsson, A.C. Eliasson and I.M.E. Björck: Resistant starch formation in temperature treated potato starches varying in amylose/amylopectin ratio. *Carbohydr. Polym.*, **65**, 306–313 (2006).
- 20) L. Li, H. Jiang, M. Campbell, M. Blanco and J. Jane: Characterization of maize amylose-extender (ae) mutant starches. Part I: Relationship between resistant starch and molecular structures. *Carbohydr. Polym.*, **74**, 396–404 (2008).
- 21) D.L. Topping, M.K. Morell, R.A. King, Z. Li, A.R. Bird and M. Noakes: Resistant starch and health—Himalaya 292, a novel barley cultivar to deliver benefits to consumers. *Starch/Stärke*, **55**,

- 539–545 (2003).
- 22) C.Z. Yang, X.L. Shu, L.L. Zhang, X.Y. Wang, H.J. Zhao, C.X. Ma and D.X. Wu: Starch properties of mutant rice high in resistant starch. *J. Agric. Food Chem.*, **54**, 523–528 (2006).
- 23) H. Fuwa, M. Nakajima and A. Hamada: Comparative susceptibility to amylases of starches from different plant species and several single endosperm mutants and their double-mutant combinations with *opaque-2* inbred Oh43 maize. *Cereal Chem.*, **54**, 230–237 (1977).
- 24) T. Noda, S. Takigawa, C. Matsuura-Endo, S.J. Kim, N. Hashimoto, H. Yamauchi, I. Hanashiro and Y. Takeda: Physicochemical properties and amylopectin structures of large, small, and extremely small potato starch granules. *Carbohydr. Polym.*, **60**, 245–251 (2005).
- 25) T. Noda, S. Takigawa, C. Matsuura-Endo, T. Suzuki, N. Hashimoto, N.S. Kottarachchi, H. Yamauchi and I.S.M. Zaidul: Factors affecting the digestibility of raw and gelatinized potato starches. *Food Chem.*, **110**, 465–470 (2008).
- 26) T. Noda, N. Isono, A.V. Krivandin, O.V. Shatalova, W. Blaszcak and V.P. Yuryev: Origin of defects in assembled supramolecular structures of sweet potato starches with different amylopectin chain-length distribution. *Carbohydr. Polym.*, **76**, 400–409 (2009).