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Characteristics of Taro (*Colocasia esculenta*) Starches Planted in Different Seasons and Their Relations to the Molecular Structure of Starch

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Physico-chemical properties and molecular structure of starches from three cultivars (Dog hoof, Mein, and KS01) of taro tubers planted in summer, winter, and spring were investigated. The effects of the planting season on the physico-chemical properties and the molecular structure of starch were determined, and the relations between the physico-chemical properties and the molecular structure of starch are discussed. Results indicate that taro starches from tubers planted in summer had the largest granule size, a low uniformity of gelatinization, and a high tendency to swell and collapse when heated in water. Taro starch planted in summer also showed an elasticity during gelatinization that was higher than that of starches planted in the other seasons. In addition to the planting season and the variety, rheological and pasting properties of taro starches studied are influenced not only by the amylose content but also by the chain-length distribution of amylopectin, whereas swelling power and solubility only depend on the amylose content of starch. Taro starch with relatively high amylose content, high short-to-long-chain ratio, and long average chain length of long-chain fraction of amylopectin displayed high elasticity and strong gel during heating.

KEYWORDS: Starch; taro; rheological properties; pasting properties; molecular structure

INTRODUCTION

Taro (*Colocasia esculenta* L. Schott) is a major tuber crop cultivated in tropical and subtropical regions of the world. In Asia, taro is used to prepare a smooth paste through the processes of steaming, peeling, and mashing. However, taros from different cultivars have different textures after being cooked and are used in different products. For example, in Taiwan, Dog hoof cultivar, which has a weak flavor, is often used for preparing taro paste or is steamed with other ingredients to provide a smooth texture. KS01 cultivar, which has a mealy texture and a strong flavor, is often consumed in lumps directly after being steamed and cut.

Starch, representing 70−80% of the dry matter, is the major component of taro tubers (*1–3*). The granule size of taro starch ranges from 1 to 5 μm, which is the smallest granule size in tuber and root starches (*2, 4*). It was found that the gelatinization properties of cocoyam (*Xanthosoma sagittifolium*) starches varied with cultural practices and planting seasons (*5*). Starch from cocoyam tubers planted in summer had significantly ($p <$ 0.05) higher average granule size, higher amylose content, higher short-to-long-chain ratio of amylopectin, and lower average degree of polymerization of the chain length.

Starch behavior has been proposed as an important factor in the texture because of several changes that take place upon gelatinization (*6, 7*). The physical properties of starch, including rheological and viscoelastic characteristics, depend on the content or structure of amylose and amylopectin (*8–11*). The viscosity and gel properties of gelatinized starch play important roles in starchy-food processing and are largely influenced by the granule shape, swelling power, amylopectin−amylose entanglement, and granular interaction of starch (*12–14*). These characteristics also depend on the molecular structure, such as amylose content or chain-length distribution of amylopectin.

It is well-known that genetic variations and environmental conditions profoundly influence the structure and properties of tuber and root starches (*14*). However, information on the physico-chemical properties and molecular structure of starches from different cultivars of taro is rare so far. The aim of this study is to elucidate the differences in physico-chemical properties of starches from three cultivars of taro tubers planted in different seasons. The relations between physico-chemical properties and molecular structure of taro starch were also

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observed, and the influence of the molecular structure on the rheological properties of starch is discussed.

MATERIALS AND METHODS

Materials. Taro tubers from three cultivars of taro, Dog hoof, Mein, and KS01, were planted and grown for the same duration during three cultivation seasons (summer, winter, and spring) in Kaohsiung District Agricultural Improvement Station, Kaohsiung, Taiwan. Taro tubers were harvested 10 months after they were planted. The cultivation durations and environment conditions were the same as those previously reported (*5*). Isoamylase (EC 3.2.1.68) from *Pseudomonas amyloderamosa* (59 000 IU/mg) was purchased from Hayashibara Biochemical Laboratories, Inc. (Tokyo, Japan). All reagents used were of analytical grade.

Isolation of Taro Starch. Taro starch was isolated according to the procedures used by Lu et al. (*5*). Taro tubers were peeled, weighed, sliced, and ground in a commercial blender with triple weight of 0.1% NaOH solution. The slurry was passed through a 250-mesh sieve and centrifuged at 3500*g* for 10 min. The sediment was suspended in water, neutralized with 0.1 N HCl solution, and centrifuged again. The sediment was then suspended in 0.1 M NaCl solution, and 10% (v/v, based on the volume of 0.1 M NaCl) toluene was added. The solution was stirred overnight at room temperature. After standing for 1 h, the suspension separated into two layers. The upper layer was a toluene−protein complex layer, and the bottom layer was a starch−water layer. The upper layer was siphoned off, and the bottom layer was centrifuged. The sediment starch was washed with distilled water to completely remove the NaCl, dehydrated with ethanol, and air-dried in an oven at 40 °C.

Chemical Composition and Average Granule Size. Crude protein (N × 6.25) and lipid contents of taro starch were measured according to the methods of AACC (*15*), whereas the amylose content of starch was determined by iodine potentiometric titration (*16*). Before evaluation of iodine affinity, the starch was defatted for 48 h with 85% methanol by Soxhlet extraction. The amylose content was calculated as follows:

$$\mathrm{AC}\,(\%) = (\mathrm{IA_S}/\mathrm{IA_{Amylose}}) \times 100$$

where AC is the amylose content, and $\mathrm{IA_S}$ is the iodine affinity of the defatted starch. Iodine affinity for pure amylose ($\mathrm{IA_{Amylose}}$) was assigned as 20%. The average granule size of starch was determined by using a laser-light scattering-based particle-size analyzer (Mastersizer Micro, Malvern Instruments, Malvern, U.K.) following the method reported previously (*17*).

Rheological Properties. A small-amplitude oscillatory rheological measurement was performed on isolated starches by using a dynamic rheometer (Carri-Med CSL^2-100 rheometer, TA Instrument Ltd., Surry, U.K.) equipped with a cone (2°)−plate geometer system (4 cm in diameter) (*18*). Yamamoto et al. (*18*) concluded that the cone−plate geometry provided uniform shear and was suited for studying non-Newtonian as well as Newtonian fluids. The strain and frequency were set at 1.0% and 1 Hz, respectively. The concentration of the starch suspension was 25% (w/w), and the temperature sweep was from 45 to 95 °C at a rate of 1 °C/min. The dynamic rheological properties, such as storage modulus (G'), loss modulus (G''), and tan δ (G''/G'), of starch during heating were determined.

Swelling Power and Solubility. Swelling power and solubility of starch were measured in the temperature range from 60 to 90 °C according to the method proposed by Leach et al. (*19*).

Pasting Properties. Pasting properties of starch were determined by using a rapid viscoanalyzer (RVA 3D$^+$, Newport Scientific, Warriewood, Australia). Each starch suspension (7% w/w, 28 g total weight) was equilibrated at 50 °C for 1 min, heated to 95 °C at a rate of 12 °C /min, maintained at 95 °C for 2.5 min, and then cooled to 50 °C at the same rate. Paddle speed was set at 960 rpm for the first 10 s and 160 rpm for the rest of the analysis. The peak viscosity (PV), hot-paste viscosity (HPV), final viscosity (FV), breakdown viscosity (BD), setback viscosity (SB), setback ratio (SB% = (SB/HPV) × 100), and breakdown ratio (BD% = (BD/PV) × 100) were quantified.

Gelatinization Thermal Properties. Thermal properties of starch during gelatinization were determined by using a differential scanning calorimeter (Micro DSC VII, Setaram, Leon, France) and by following the method described by Chang et al. (*20*). Starch was weighed into a stainless-steel sample pan and mixed with distilled water (dry starch: water = 1:3). The pan was sealed, and the solution was equilibrated at room temperature for 1 h and scanned at a heating rate of 1.2 °C/min from 25 to 115 °C. The onset (T_o), peak (T_p), and conclusion (T_c) temperatures, gelatinization enthalpy (ΔH), and gelatinization range ($T_r = T_c - T_o$) were quantified. The peak high index (PHI = $\Delta H/T_r$) of starch was also determined (*20*).

Chain-Length Distribution. Starch, after being debranched by isoamylase, was filtered through a 0.45 μm nylon syringe filter, and the chain-length distribution of starch was determined by using a high-performance size-exclusion chromatography (HPSEC) system (*17*). The system consisted of an HP G1310A isocratic pump (Hewlett-Packard, Wilmington, DE), a refractive index (RI) detector (HP 1047A), and a multiangle laser-light scattering (MALLS) detector (Dawn DSP, Wyatt Tech., Santa Barbara, CA) equipped with one G3000PW$_{XL}$ and two G2500PW$_{XL}$ columns (TSK-Gel, Tosoh, Tokyo, Japan). The mobile phase was 100 mM phosphate buffer (pH 6.2) containing 0.02% sodium azide, and the flow rate was 0.5 mL/min. A typical HPSEC profile of debranched starch showed a trimodal distribution. The molecular weight of the first peak (amylose) was determined by using MALLS and RI signals, and the molecular weights of the second and third peaks (long chain and short chain of amylopectin, respectively) were calculated from the RI signals by using a calibration curve constructed from a series of pullulan standards with molecular weights ranging from 1.0 to 47.3 kDa (Polymer Standards Service, Silver Spring, MD). Triplicate determinations were done for each sample.

Statistical Analysis. Statistical comparisons of means and simple correlation coefficients were conducted by using the Student's t test in the general linear model procedure of a SAS system (SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Chemical Composition and Average Granule Size of Starch. As shown in **Table 1**, protein and lipid contents of taro starches ranged from 0.04 to 0.06% and from 0.08 to 0.12% (dry-weight basis), respectively. This reveals the high purity of taro starches. The amylose content of taro starch was affected by the planting season and ranged from 10.2 to 13.4, 12.0 to 14.9, and 8.7 to 13.2% for Dog hoof, Mein, and KS01 cultivars, respectively. The amylose content of starch was proposed to be affected by the planting season and environment temperature for different starchy crops (*22–25*). For the same cultivar of taro, tubers planted in spring had the lowest content of amylose among the contents measured during the three planting seasons in this study. According to the atmospheric temperature during the growth period (*5*), taro tubers planted in spring had the lowest atmospheric temperature for tuber development. This implies that the low amylose content of starch from taro tubers developing at lower temperatures could be observed. Similar results were observed for sweet-potato starch and microtuber starch for growth at different temperatures (*25, 26*). In addition to atmospheric temperature, the variation in total rainfall during the growth period from the 4th to the 10th month has been proposed to influence the physico-chemical properties of cocoyam starch (*5*).

Taro starches showed unimodal distribution profiles for the granule size determined by the laser-light particle-size analyzer, and the average granule-size values corresponded to the principal peaks. The average granule size of starches from the three cultivars of taro planted in different seasons ranged from 2.37 to 2.79 μm. This indicates that the granule size of taro starch is obviously smaller than that of potato, corn, or tapioca starches but is similar to that of rice starch (*22*). For the same cultivar

Table 1. Chemical Composition and Average Granule Size of Taro Starches[a]

season	crude protein (%, d.b.)	crude lipid (%, d.b.)	amylose (%, d.b.)	average granule size (μm)
		Dog hoof		
summer	0.06 a ± 0.00	0.08 a ± 0.01	13.4 a ± 0.1	2.75 a ± 0.03
winter	0.04 a ± 0.01	0.09 a ± 0.02	11.3 b ± 0.2	2.42 c ± 0.05
spring	0.04 a ± 0.01	0.09 a ± 0.00	10.2 c ± 0.1	2.68 b ± 0.03
		Mein		
summer	0.05 a ± 0.01	0.11 a ± 0.01	13.3 b ± 0.2	2.54 a ± 0.04
winter	0.05 a ± 0.01	0.10 a ± 0.01	14.9 a ± 0.1	2.44 b ± 0.03
spring	0.05 a ± 0.01	0.09 a ± 0.00	12.0 c ± 0.2	2.47 b ± 0.01
		KS01		
summer	0.05 a ± 0.01	0.10 a ± 0.01	13.2 a ± 0.2	2.79 a ± 0.01
winter	0.04 a ± 0.00	0.12 a ± 0.01	9.7 b ± 0.1	2.37 c ± 0.01
spring	0.04 a ± 0.00	0.11 a ± 0.01	8.7 c ± 0.1	2.46 b ± 0.02

[a] Means with different letters in the same column within the same cultivar differ significantly ($p < 0.05$), $n = 3$.

Table 2. Rheological Properties during Heating of Taro Starches[a]

season	$T_{G'}$ (°C)	$T_{G'\max}$ (°C)	$G'_{\max}$ (Pa)	tan $\delta_{G'\max}$	G'_{90} (Pa)	G'_{BD}[b]
			Dog hoof			
summer	69.6 c	72.4 c	2819 a	0.26 b	784 b	0.72 a
winter	77.0 a	79.4 a	1209 b	0.27 ab	1078 a	0.10 c
spring	71.2 b	75.1 b	1064 c	0.29 a	738 c	0.31 b
			Mein			
summer	70.4 c	72.3 c	1477 a	0.25 b	630 b	0.57 a
winter	73.7 b	82.3 b	873 b	0.30 a	680 a	0.22 c
spring	75.2 a	84.2 a	860 b	0.26 b	624 b	0.27 b
			KS01			
summer	66.3 c	69.6 c	1589 a	0.25 c	454 b	0.71 a
winter	74.2 a	76.2 b	856 b	0.30 a	602 a	0.30 c
spring	71.5 b	79.7 a	870 b	0.28 b	424 c	0.51 b

[a] Means with different letters in the same column within the same cultivar differ significantly ($p < 0.05$), $n = 3$. [b] $G'_{BD} = (G'_{\max} - G'_{90})/G'_{\max}$.

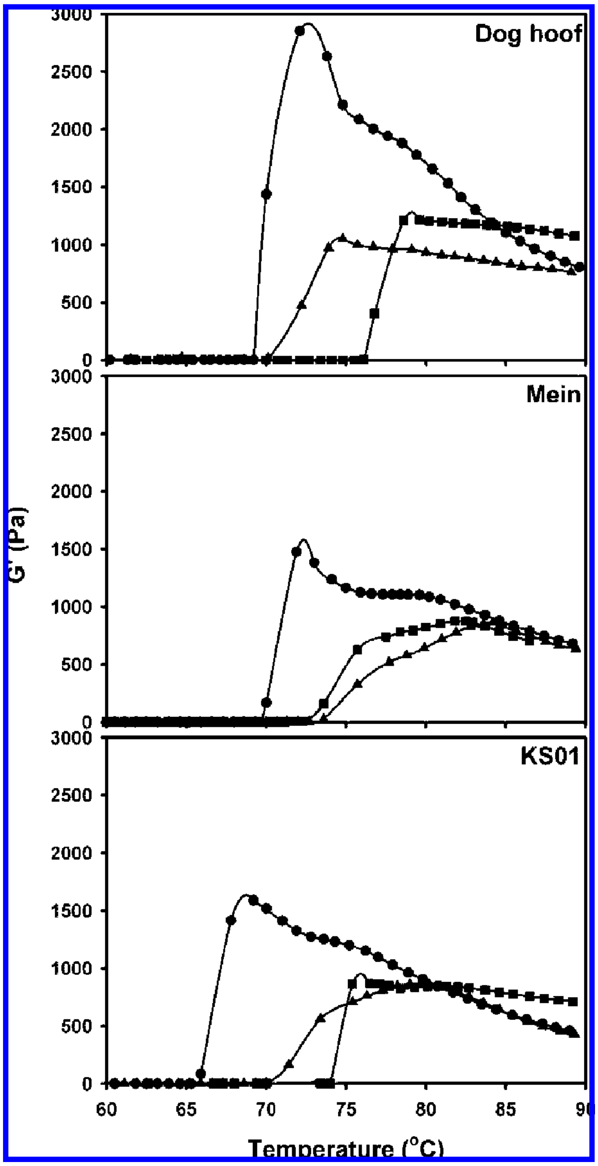

Figure 1. Storage modulus (G') of starches from taro tubers planted in summer (●), winter (■), and spring (▲).

of taro, the average size of starch granules from tubers planted in summer was larger than that of tubers planted in the other two seasons. This agrees with the results of a previous study on cocoyam starch (*5*).

Rheological Properties of Starch. The rheological properties of taro starches during heating were determined by dynamic rheometry; **Table 2** summarizes the results of our observations. The G' of taro starch during heating was lower than 10 Pa at a temperature below $T_{G'}$ and rapidly increased thereafter (**Figure 1**), which indicates the transformation of starch suspension into a sol (*24*). Taro starches from tubers planted in summer had the lowest $T_{G'}$ among those of the starches from tubers planted in the different seasons. Furthermore, $T_{G'\max}$, the temperature at which the maximum G' occurred, of taro starches ranged from 72.4 to 79.4, 72.3 to 84.2, and 69.6 to 79.7 °C for Dog hoof, Mein, and KS01 cultivars, respectively. Starches from tubers planted in summer also had the lowest $T_{G'\max}$ among those of the tubers planted in the different seasons. The results imply that taro starches from tubers planted in summer swell more easily when heated in the presence of water than starches from tubers planted in the other two seasons.

The maximum G' value ($G'_{\max}$) during heating of starch from tubers planted in summer was obviously higher than those of starches planted in the other two seasons. The value of tan $\delta_{G'\max}$ for starch from tubers planted in summer was also significantly lower than those for starches planted in the other two seasons. Moreover, taro starch from Dog hoof cultivar planted in summer had the highest $G'_{\max}$ among those of the starches studied. The G' of taro starches at 90 °C (G'_{90}) varied with the cultivars and planting seasons. The value of G'_{90} for taro starch from Dog hoof cultivar was higher than those for the other two cultivars of taro. Starch from tubers planted in winter showed the highest G'_{90} among those of the tubers planted in the different seasons. G'_{BD}, which is the decreasing ratio of G' at temperatures between $T_{G'\max}$ and 90 °C, could be attributed to the collapse of gelatinized starch granules when the starch is continuously heated at a temperature higher than the gelatinization temperature. For each cultivar, the G'_{BD} values of starches from tubers planted in different seasons are in the following order: summer > spring > winter.

Results in **Table 2** denote that the rheological properties of taro starches depend not only on the cultivar of taro but also on the planting season. The values of $T_{G'}$ and $T_{G'\max}$ for starches from taro tubers planted in summer were low , and a high $G'_{\max}$ and G'_{BD} and a low $\tan \delta_{G'\max}$ were observed for the starch gels. Sodhi and Singh (*27*) indicated that rice starch with high amylose content displayed a high peak G' ($G'_{\max}$) during heating. The same is true for potato starches from different cultivars (*28*). However, results in some reports (*2728*) also showed that starches with similar amylose contents had obviously different rheological properties, such as $G'_{\max}$. This implies that other factors in addition to amylose content, such as granule structure or molecular structure of starch, could influence the rheological properties of starch, especially for starches with close amylose contents. The high $G'_{\max}$ and low $\tan \delta_{G'\max}$ of taro starches from tubers planted in summer could be attributed to their large granule size compared to the starches planted in the other seasons. At temperatures above $T_{G'\max}$, the value of G'_{BD} for starches from tubers planted in summer was higher than those for tubers planted in the other two seasons. Generally, the rigidity of gelatinized starch is strongly dependent on the amylose content of starch (*29*). However, the amylose contents of taro starches studied in this report were in a narrow range; thus, the difference in G'_{BD} of different starches could result from other factors, such as the chain-length distribution of starch (*21*).

Swelling Power and Solubility of Starch. The taro starches studied showed similar swelling power (**Figure 2**) and solubility patterns (**Figure 3**). The taro starches had very low swelling power and solubility at temperatures below 70 °C; those quantities increased with increasing temperatures above 70 °C. For Dog hoof and Mein cultivars, less obvious differences in swelling powers or solubilities among starches from tubers planted in the different seasons were found. This could be attributed to the similar amylose content (<3.5% difference) of starches planted in the different seasons for Dog hoof and Mein cultivars. The swelling power and solubility of KS01 starches depend on the planting season, especially when measured at 90 °C. The swelling power and solubility values of KS01 starches at 90 °C are in the following order: spring > winter > summer, which confirms that starch with a higher amylose content displayed a lower swelling power and solubility (*30*). Li and Yeh (*31*) indicated that the swelling of starch granules was related to their pasting behavior and rheological properties. However, the rheological properties of taro starches investigated in this study did not show obvious relations with their swelling powers. This indicates that, except for the swelling of starch during heating, there are other factors that could affect the rheological properties of starch, such as the molecular structure of starch (*21, 32*).

Gelatinization Thermal Properties of Starch. The thermal transition profiles of taro starches determined by DSC are shown in **Figure 4**. Taro starches from tubers planted in summer showed bimodal distribution profiles, whereas single sharp profiles were observed for Dog hoof and KS01 starches from tubers planted in winter. Ji et al. (*33*) indicated that subpopulations with different physical and chemical properties, such as gelatinization behaviors, existed in waxy maize starch from a single original source, which could be attributed to the molecular structure differences among different starch granules. Therefore, the bimodal distribution profile of the taro starch planted in summer might be attributed to its more heterogeneous granules with high variation of gelatinization behaviors and granular structures. The planting season significantly affected T_o and T_p of taro starches (**Table 3**). The values of T_o and T_p for taro starches from tubers planted in summer were lower than those for tubers planted in the other two seasons. The values of T_r for taro starch planted in different seasons were in the following order: summer > spring > winter. The effect of the planting season on the gelatinization temperature of taro starch is in line with that on cocoyam starch (*5*). ΔH was greater for starches from tubers planted in winter. The values of PHI, referring to the gelatinization uniformity of starch (*20, 34*), for taro starches from tubers planted in different seasons were in the order reverse to those of T_r.

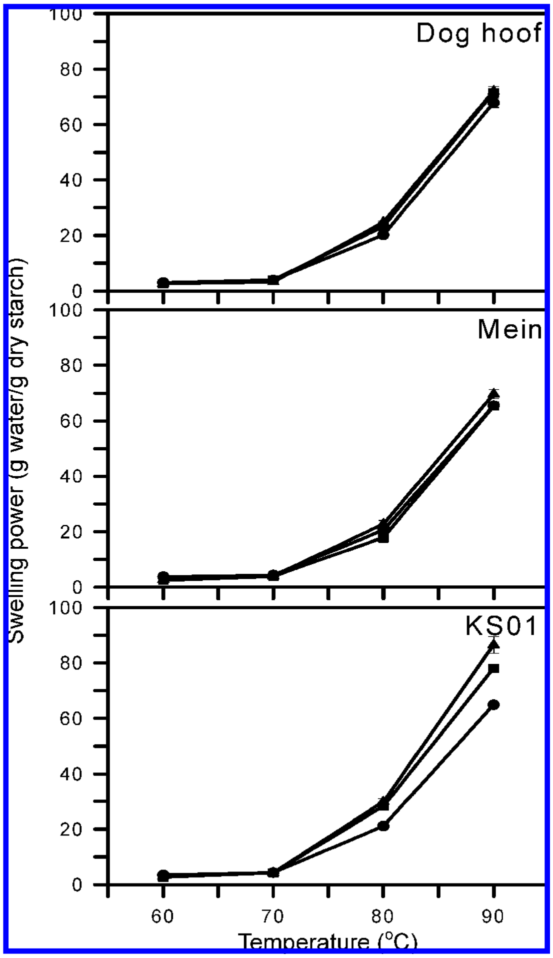

Figure 2. Swelling power of starches from taro tubers planted in summer (●), winter (■), and spring (▲).

Results indicated that taro starches from tubers planted in summer had the lowest T_o, T_p, ΔH, and PHI and the highest T_r. Furthermore, a smaller difference in gelatinization thermal properties between starches from tubers planted in winter and spring was found. The low gelatinization temperature of starches from tubers planted in summer could reflect their low $T_{G'}$ and $T_{G'\max}$ and high G'_{BD} during heating (**Table 2**).

Pasting Properties of Starch. The pasting peak viscosity of Dog hoof taro starch was lower than those of the other cultivars planted in the same season (**Table 4**). The values of PV, HPV, FV, and BD for starches from taro tubers planted in spring were higher than those for tubers planted in the other two seasons. Moreover, the SB% of starch planted in summer was the highest. The high pasting viscosity of starch planted in spring could be attributed to its lower amylose content. However, the BD% and SB% of starch did not show any obvious relation to the amylose

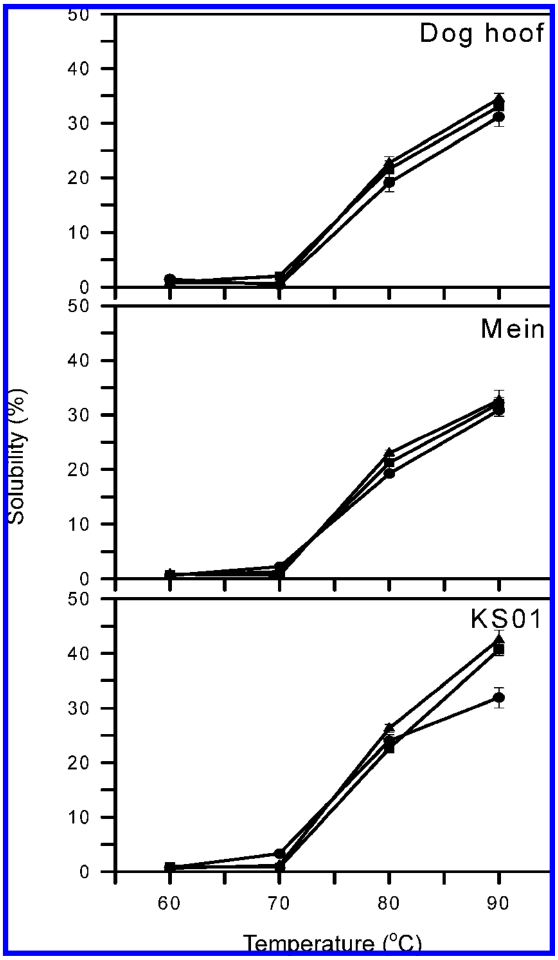

Figure 3. Solubility of starches from taro tubers planted in summer (●), winter (■), and spring (▲).

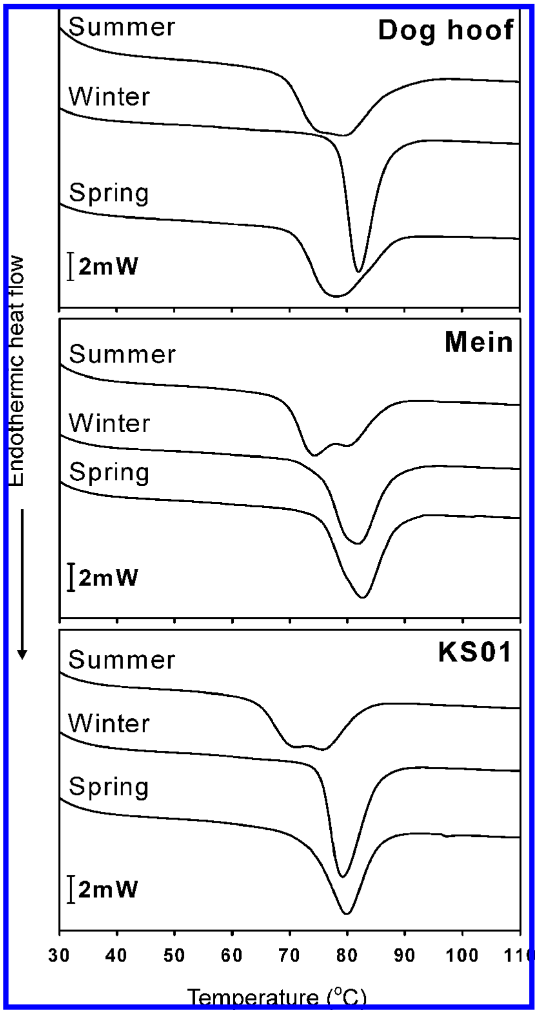

Figure 4. DSC thermograms of starches from taro tubers planted in different seasons.

Table 3. Gelatinization Thermal Properties of Taro Starches[a]

	gelatinization temperatures (°C)[b]					
season	T_o	T_p	T_c	T_r[c] (°C)	ΔH[d] (J/g)	PHI[e]
			Dog hoof			
summer	69.2 c	79.2 c	88.4 a	19.2 a	17.0 b	0.887 c
winter	78.7 a	81.9 a	87.3 b	08.6 c	18.2 a	2.117 a
spring	77.3 b	80.9 b	88.5 a	11.2 b	17.2 b	1.536 b
			Mein			
summer	69.3 c	74.3 c	87.2 c	17.8 a	16.9 b	0.948 c
winter	75.4 b	81.7 b	88.0 b	12.6 c	17.7 a	1.400 a
spring	75.5 a	82.6 a	88.4 a	12.9 b	17.5 a	1.353 b
			KS01			
summer	64.5 c	75.6 c	82.8 b	18.3 a	15.8 c	0.864 c
winter	75.4 a	79.2 b	85.4 a	10.0 c	17.8 a	1.790 a
spring	73.3 b	79.8 a	85.4 a	12.1 b	16.4 b	1.353 b

[a] Means with different letters in the same column within the same cultivar differ significantly ($p < 0.05$), $n = 3$. [b] T_o, T_p, and T_c are the onset, peak, and conclusion temperatures of gelatinization. [c] Gelatinization temperature range. [d] Enthalpy of gelatinization. [e] Peak high index, $\Delta H/T_r$.

content of starch. Han and Hamaker (*35*) indicated that the pasting properties of rice starches with a fairly narrow range of amylose content (15.1−17.9%) were dependent on the chain-length distribution of amylopectin. In this study, the amylose content of taro starch ranged from 8.7 to 14.9%; thus, the pasting properties of taro starches in this study could be affected not only by the amylose content of starch but also by the structure of amylopectin.

Chain-Length Distribution of Debranched Starch. The chain-length distributions of taro starches show trimodal profiles (**Figure 5**) and can be divided accordingly into three fractions. The fractions from low to high elution volume correspond to amylose (f1), long chains (f2), and short chains (f3) of amylopectin, respectively. **Table 5** summarizes the weight percentage and the weight-average chain length (CL_w) of each fraction of taro starches studied. Results showed that the weight percentage of f1 (f1%) of taro starches ranged from 10.2 to 19.3%. The value of f1% for starches from tubers planted in spring was lower than those for tubers planted in the other two seasons. Although the amylose content (f1%) value of starch determined by HPSEC was higher than that determined by iodine potentiometric titration (**Table 1**), results of the two methods showed the same trend. A similar result was found for cocoyam starch (*5*) and taro starch (*2*). Discrepancies between the two methods can be attributed to the intermediate components, such as molecules with branched structures and smaller molecular size than amylopectin, which might elute at the same time as amylose during the HPSEC determination (*2*). The f2% and f3% of starch ranged from 20.4 to 26.5 and 58.7 to 64.7, respectively. Taro starches from tubers planted in summer had the lowest f2% value among starches from tubers planted in the different seasons. For each cultivar of taro, starches from tubers planted in summer had the highest *S*/*L*, which is the weight percentage ratio of short-to-long-chain fractions of amylopectin. This reveals that the amylopectin molecules of starches from tubers planted in summer have

Table 4. Pasting Properties of Taro Starches[a]

season	viscosity (cP)[b] PV	HPV	FV	BD	SB	SB%[c]	BD%[d]
			Dog hoof				
summer	755 c	600 b	1051 b	155 b	451 b	75 a	21 b
winter	829 b	609 b	918 c	220 a	309 c	51 c	27 a
spring	1104 a	885 a	1482 a	219 a	597 a	67 b	20 b
			Mein				
summer	1023 b	735 b	1250 ab	288 a	514 a	70 a	28 a
winter	903 c	704 b	1175 a	199 b	482 b	69 a	22 c
spring	1139 a	857 a	1283 b	282 a	426 c	50 b	25 b
			KS01				
summer	927 c	637 c	1152 a	290 c	515 a	81 a	31 b
winter	1056 b	733 b	1082 b	323 b	349 c	48 c	31 b
spring	1321 a	784 a	1190 a	537 a	407 b	52 b	41 a

[a] Means with different letters in the same column within the same cultivar differ significantly ($p < 0.05$), $n = 3$. [b] PV, peak viscosity; HPV, hot paste viscosity; FV, final viscosity; BD, breakdown viscosity; and SB, setback viscosity. [c] SB% = (SB/HPV) × 100. [d] BD% = (BD/PV) × 100.

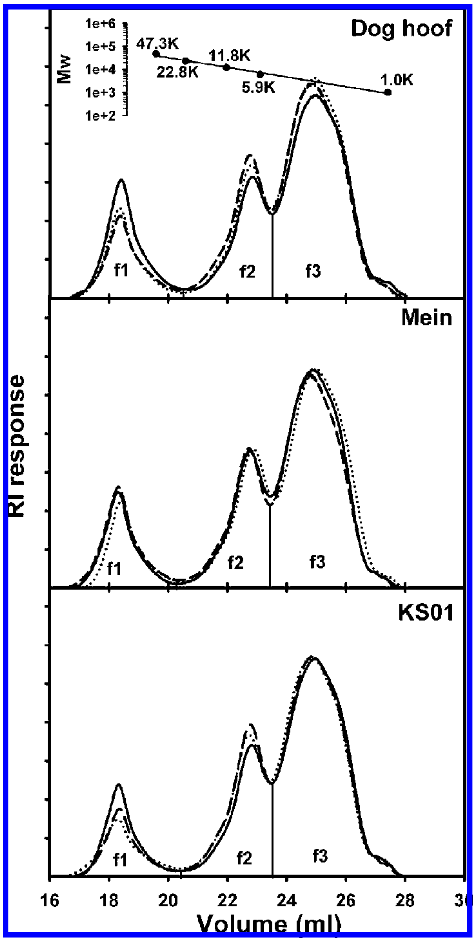

Figure 5. HPSEC profiles of starches after being debranched by isoamylase. Starches were isolated from taro tubers planted in summer (solid line), winter (dashed line), and spring (dotted line).

Table 5. Weight Percentage and Average Chain Length (CL_w) of Taro Starches after Isoamylase Debranching[a]

season	weight percentage (%) f1	f2	f3	S/L[b]	CL_w[c] f1	f2	f3
				Dog hoof			
summer	19.3 a	20.4 c	60.4 b	2.92 a	2297 a	54.8 c	16.1 a
winter	13.8 b	22.3 b	63.9 a	2.89 a	2320 a	56.5 b	16.3 a
spring	12.9 b	25.3 a	61.8 b	2.46 b	1734 b	58.0 a	15.9 a
				Mein			
summer	14.6 b	22.9 b	62.5 a	2.79 a	2016 b	57.4 b	16.4 a
winter	16.8 a	24.5 a	58.7 b	2.41 b	1763 c	58.7 a	16.7 a
spring	13.0 c	24.8 a	62.2 a	2.53 b	2099 a	54.1 c	15.2 b
				KS01			
summer	14.2 a	22.6 c	63.2 b	2.86 a	2053 b	55.3 b	15.9 a
winter	11.0 b	26.5 a	62.4 b	2.36 c	1982 b	57.9 a	16.2 a
spring	10.2 b	25.1 b	64.7 a	2.59 b	2158 a	56.3 b	15.8 a

[a] Means with different letters in the same column within the same cultivar differ significantly ($p < 0.05$), $n = 3$. [b] *S/L* = f3%/f2%. [c] CL_w, weight-average chain length.

relatively more short chains. The chain lengths of starch molecules ranged from 1734 to 2320, 54.1 to 58.7, and 15.2 to 16.7 for f1, f2, and f3 fractions, respectively. Starches planted in different seasons had different chain lengths for f1 and f2, and the chain lengths varied with different cultivars.

Tester et al. (*36*) indicated that the amylose content of potato starch decreased as the growth temperature increased from 10 to 20 °C. In this study, taro tubers were harvested after 10 months; the environment temperature during the period of 2−3 months before harvesting for tubers planted in spring (19−20 °C) was significantly lower than that for tubers planted in the other two seasons (>25 °C) (*5*). The amylose content (**Tables 1** and **5**) of starch planted in spring, which was obviously lower than those of starches planted in the other two seasons, agrees with the results of Tester et al. (*36*). The results also indicate that taro tubers planted at a lower environment temperature had starch with a relatively lower amylose content. As mentioned, the amylopectin of starches from tubers planted in summer had more short chains (higher *S/L*) than those from tubers planted in the other two seasons. This implies that the starches from tubers planted in summer tend to swell and collapse during gelatinization (*35*), and this hypothesis is confirmed by the rheological result of this study, that is, higher values of G'_{max} and G'_{BD} were observed for starches from tubers planted in summer (**Table 2**).

Relations between Physico-chemical Properties and Molecular Structure of Starch. Results of this study show that taro starches planted in various seasons differ significantly in their physico-chemical properties, such as rheological properties, swelling power, pasting properties, and gelatinization properties. Although the amylose content of starch has been reported to play an important role in its physico-chemical properties, especially rheological properties, swelling power, and pasting properties (*8, 10, 14*), the difference in amylose content among the taro starches studied was too small to explain the discrepancy in their physico-chemical properties. Therefore, other factors, such as molecular structure, should be taken into account to explain the diversity of physico-chemical properties observed.

Table 6 summarizes the correlations between physico-chemical properties and parameters of starch molecular structure in addition to varieties and planting seasons of the taro tubers. The G'_{max} of taro starch was positively correlated with f1% and *S/L* ($p < 0.05$) and negatively correlated with f2% ($p < 0.01$), whereas tan $\delta_{G'max}$ showed a positive correlation with f2% and f2CL_w and a negative correlation with *S/L* ($p < 0.05$). This result implies that taro starch with relatively higher amylose content, higher *S/L* (fewer long chains), and longer average chain-length of amylopectin long-chain fraction displays a more elastic and stronger gel during heating. The gelatinization thermal parameters did not show any significant correlation with the parameters of the molecular structure ($p > 0.05$). The swelling power and solubility of taro starch measured at 80 and 90 °C were negatively correlated with f1% ($p < 0.05$), and the swelling power determined at 80 °C was positively correlated with f3%

Table 6. Correlations between Physico-chemical Properties and Molecular Structure of Taro Starch[a]

	weight percentage (%)				CL_w		
parameter	f1	f2	f3	*S*/*L*	f1	f2	f3
				Rheological Properties			
TG′	a	a	a	a	a	a	a
TG'_{max}	a	a	a	a	a	a	a
G'_{max}	0.755 b	−0.868 c	a	0.794 b	a	a	a
$\tan \delta_{G'max}$	a	0.693b	a	−0.771b	a	0.699 b	a
G'_{90}	a	a	a	a	a	a	a
G'_{BD}	a	a	a	a	a	a	a
				Gelatinization Thermal Properties			
T_o	a	a	a	a	a	a	a
T_p	a	a	a	a	a	a	a
T_c	a	a	a	a	a	a	a
T_r	a	a	a	a	a	a	a
ΔH	a	a	a	a	a	a	a
PHI	a	a	a	a	a	a	a
				Swelling Power			
60 °C	a	a	a	a	a	a	a
70 °C	a	a	a	a	a	a	a
80 °C	−0.859 c	a	0.680 b	a	a	a	a
90 °C	−0.740 b	a	a	a	a	a	a
				Solubility			
60 °C	a	a	a	a	a	a	a
70 °C	a	a	a	a	a	a	a
80 °C	−0.767 b	a	a	a	a	a	a
90 °C	−0.783 b	a	a	a	a	a	a
				Pasting Properties			
PV	−0.822 c	0.742 b	a	a	a	a	a
HPV	a	0.741b	a	−0.709 b	a	a	a
FV	a	a	a	a	−0.715 b	a	a
BD	−0.817 c	a	0.694 b	a	a	a	a
SB	a	a	a	a	a	a	a
BD%[b]	−0.686 b	a	0.756 b	a	a	a	a
SB%[b]	0.674 b	a	a	a	a	a	a

[a] a, b, and c stand for $p > 0.05$, $p < 0.05$, and $p < 0.01$, respectively. [b] SB% = (SB/HPV) × 100; BD% = (BD/PV) × 100.

($p < 0.05$). This reveals that taro starch with a low content of amylose tends to swell and form a solute in water at heating temperatures above 80 °C. PV and BD% of pasting properties were negatively correlated with f1% ($p < 0.05$), whereas SB% and f1% showed a positive correlation ($p < 0.05$). PV and HPV and BD and BD% were positively correlated with f2% and f3% ($p < 0.05$), respectively. Negative correlations between HPV and *S*/*L* and between FV and CL_w of f1 (f1CL_w) were also observed. The content (weight percentage) of each fraction of chain-length distribution accounts for different parameters of the pasting properties. Taro starch with a high content of amylose (f1%) showed restricted pasting during heating and was easy to set back during cooling, whereas starch with a high content of long-chain fraction of amylopectin (f2%) showed a high PV and HPV during heating. Moreover, the content of short-chain fraction of amylopectin (f3%) was responsible for the granule stability of gelatinized starch. Amylopectin of starch with more short chains tended to collapse when heated in water; therefore, high BD and BD% were observed.

In this study, the physico-chemical properties of taro starches from tubers planted in different seasons were observed and compared. The planting season strongly influences the physico-chemical properties of taro starch. In addition to differences among cultivars of taro, starches from tubers planted in summer showed properties different from those of tubers planted in the other two seasons. Taro starches from tubers planted in summer had the highest average granule size, less uniformity of gelatinization (the highest PHI), and higher tendency to swell and collapse at high temperatures when heated in water. The rheological and pasting properties of the taro starches studied are influenced by both the amylose content and the chain-length distribution of amylopectin, whereas swelling power and solubility only depend on the amylose content of starch. No obvious trend between gelatinization thermal properties and molecular structure of taro starch was found. This could be attributed to the narrow molecular-structure distribution or small sample size of taro starch in this study. On the basis of the data presented, taro starches with different properties could be cultivated from the same cultivar of taro and could be used for different applications, such as thickening or gelling agents (*37*). Nevertheless, the effect of environment conditions on the synthesis of starch granules and the influence on the physico-chemical properties of starch need to be studied in depth.

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