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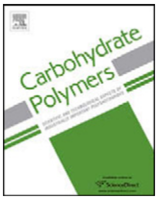

Freeze–thaw stability of starches from different botanical sources: Correlation with structural features

Sathaporn Srichuwong[a,1,2], Naoto Isono[a,*,1], Hongxin Jiang[b], Takashi Mishima[a], Makoto Hisamatsu[a]

[a] *Graduate School of Bioresources, Mie University, Tsu 514-8507, Japan*
[b] *Department of Food Science and Human Nutrition, Iowa State University, Ames, IA 50011, USA*

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ABSTRACT

Native starches from twenty-six botanical sources were determined for their structural features and stability against freeze–thaw treatments. Starch gels (5%, w/w) were prepared and repeatedly freeze–thawed up to five cycles by storing at −18 °C for 21 h and then at 30 °C for 3 h. Water release (syneresis) from the thawed gel after the 1st, 3rd and 5th cycle was measured gravimetrically, and evaluated in relation to apparent amylose content (AAC) and distribution of amylopectin branch chains with degree of polymerization 6–12 (APC ratio). Syneresis was not observed for starch gels of cassava, normal and waxy japonica rice up to the 1st, 3rd and 5th cycle, respectively. On the other hand, syneresis rapidly occurred for starch gels of elephant yam, new cocoyam, potato, edible canna, and water yam. Optimal multiple linear regression models were generated to predict individual effect of AAC and APC ratio on syneresis of starch gels. The prediction models illustrated the positive unit-contribution of AAC and negative unit-contribution of APC ratio to syneresis ($P < 0.001$).

1. Introduction

Starch is a major energy source of human diet and is an important texture modifier in many food products because of its thickening and gelling properties. Starch granules are principally composed of two glucose polymers, amylose and amylopectin. In starch granules, a dense packing of amylopectin double helices forms semicrystalline structures, whereas amylose molecules are amorphous (Jane, 2009). By heating the starch granules with excess water above gelatinization temperature, several events take place including crystallite melting, granular swelling, leaching of some amylose molecules, and changes in extent of molecular entanglement and rearrangement. This phenomenon results in viscous dispersion, solution, paste or gel, depending on concentration of starch and temperature. Accordingly, starch gels are composites of swollen-deformable granules, granular fragments and continuous matrix of entangled amylose molecules, holding water within a network (Biliaderis, 2009; Miles, Morris, Orford, & Ring, 1985). In general, food applications of native starches are limited by their instability against thermal processing, shear, pH and cold storage, commonly applied to processed foods. Despite these limitations, more and more food producers are following the current trends of natural, non-chemically modified and clean-label ingredients, and offering their products with a list of ingredients free from additives (Thomas, 2009). The trends have promoted the use of native and physically modified starches instead of chemically modified starches.

Starch has been incorporated in many foods including sauce, soup, frozen-batter, ice cream, cream-based product, and dessert. These products usually expose to series of temperature fluctuation during long-term storage or freeze–thaw process before consumption. For the frozen food products, a stability of starch upon freeze–thaw process is very important to guarantee textural quality of the product after production and distribution chain. During freezing, starch concentration increases as ice crystals grow; eventually a maximally freeze-concentrated solution matrix is formed. The unfrozen matrix at a constant solute concentration exists as kinetically metastable and amorphous solid at temperatures below glass transition temperature (T_g) (Wang & Jane, 1994). A temperature fluctuation above T_g during repeating freeze–thaw cycles accelerates retrogradation of starch molecules in the starch-rich phase, enhancing the phase separation. Eventually, the ice crystals are embedded in a sponge-like structure, coarsely aggregated starch network. Upon thawing, the ice melts to water that readily separated from the matrix, giving rise to a phenomenon known as syneresis (Eliasson & Kim, 1992; Rahman, 1999; Yaun & Thompson, 1998). Accordingly, the rate of starch retrogradation

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Abbreviations: AAC, apparent amylose content; APC ratio, amylopectin unit-chain ratio; FTC, freeze–thaw cycle; MLR, multiple linear regression.

[*] Corresponding author. Tel.: +81 59 231 9613; fax: +81 59 231 9613.
E-mail address: isono@bio.mie-u.ac.jp (N. Isono).

[1] Contributed equally to this work.

[2] Present address: Nestlé Research Center, Vers-chez-les-Blanc, P.O. Box 44, CH-1000 Lausanne 26, Switzerland.

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contributes considerably to freeze–thaw stability. Starch retrogradation is influenced by botanical source, molecular composition and structure, temperature fluctuation, and concentration of starch gel. Presences of maltodextrins, sugars and salts also influence starch retrogradation by shifting glass transition temperature of the freeze-concentrated solution (Baker & Rayas-Duarte, 1998; Wang & Jane, 1994). Addition of hydrocolloids and increased freezing rate are also reported to reduce syneresis of native starch gels (Muadklay & Charoenrein, 2008).

For native starches, the freeze–thaw stability is one of the key determinants for their use as the clean-label ingredients in frozen food products. It has been shown that syneresis varies considerably according to botanical source of starches (Praznik, Mundigler, Kogler, Pelzl, & Huber, 1999; Takeiti, Fakhouri, Ormenese, Stell, & Collares, 2007; Yaun & Thompson, 1998). Although being a minor component in starch granules, amylose is known to undergo retrogradation at a higher rate than amylopectin; however, the contribution of amylose content to syneresis of starch gels is not clear. Greater syneresis was reported with higher amylose content for corn and potato starches (Sandhu & Singh, 2005; Singh, Kaur, & Singh, 2004); however, no significant correlation between amylose content and syneresis was observed for rice starches (Singh, Kaur, Sandhu, Kaur, & Nishinari, 2006; Wang et al., 2010). Waxy (amylose-free) starch gels, in general, are more resistant to syneresis than their normal counterparts. Waxy starch gels may remain very stable for weeks to months under refrigerated conditions, but the stability breaks down quickly after freeze-thawing (Schoch, 1968). With increase in the number of freeze–thaw cycles, syneresis of waxy starch gel increases, which is attributed to amylopectin retrogradation (Yaun & Thompson, 1998; Zheng, Han, & Bhatty, 1998). A study on genetically modified potatoes showed that waxy starch having shorter amylopectin branch chains was more resistant to syneresis (Jobling, Westcott, Tayal, Jeffcoat, & Schwall, 2002). Accordingly, freeze–thaw stability of starch gels is influenced by amylose content and amylopectin branch chain length; however, their relationships have not been established. The aims of this work were to investigate the influence of botanical sources on freeze–thaw stability of native starch gels, and evaluate the contribution of structural features to syneresis.

2. Materials and methods

2.1. Materials

Twenty-six starches from different botanical sources were used in this study. A wet-milling method was used for isolating starches from the following tubers and roots; elephant yam (*Amorphophallus paeoniifolius*), new cocoyam (*Xanthosoma sagittifolium*), taro (*Colocasia esculenta*), water yam (*Dioscorea alata*), lesser yam (*Dioscorea esculenta*), yam bean (*Pachyrhizus erosus*), edible canna (*Canna edulis*), arrowroot (*Maranta arundinacea*) and lotus root (*Nelumbo nucifera*), as described previously (Srichuwong, Sunarti, Mishima, Isono, & Hisamatsu, 2005a). These tubers and roots were collected from farms in Indonesia and Thailand. The lotus roots were freshly collected from a farm in Tatsuta, Japan.

A dilute alkaline steeping method (Wang & Wang, 2001) was employed for isolating starches from three wheat cultivars (*Triticum aestivum*) (cv. Norin61, Haruyutaka and 1CW) collected from an experimental farm in Hokkaido, Japan; mung bean (*Vigna radiata*), normal japonica rice (*Oryza sativa*) cv. Koshihikari, and waxy japonica rice cv. Hakuchomochi purchased from local markets in Tsu, Japan; job's tears (*Coix lacryma-jobi*) and normal indica rice purchased from local markets in Chiang Mai, Thailand; and lotus seeds (*Nelumbo nucifera*) freshly harvested from the farm in Tatsuta, Japan.

Commercial starches including sweet potato (*Ipomoea batatas*), kudzu (*Pueraria lobata*), sago (*Metroxylon sagu*), cassava (*Manihot esculenta*), normal corn (*Zea mays*), waxy corn, normal japonica rice cv. Nipponbare, and potato (*Solanum tuberosum*) were obtained from Nihon Shokuhin Kako Co., Ltd. (Tokyo, Japan). Crystalline isoamylase (EC 3.2.1.68) from *Pseudomonas amyloderamosa* was purchased from Hayashibara Biochemical Laboratories, Inc. (Okayama, Japan). The fluorescence labeling agent, 8-amino-1,3,6-pyrenetrisulfonic acid (APTS), was purchased from Sigma–Aldrich Co. (St Louis, MO, USA). All chemicals were reagent grade and obtained from Sigma–Aldrich Co. (St. Louis, USA).

2.2. Apparent amylose content

Apparent amylose content (AAC) of starch was determined according to the method of Takeda, Hizukuri and Juliano (1987). Starch was defatted by dispersing in dimethylsulfoxide followed by ethanol precipitation. Iodine affinity of the defatted starch was determined using a potentiometric titration. AAC was calculated by dividing the iodine affinity value of defatted starch by the value obtained from a purified potato amylose (A0512, Sigma–Aldrich Co., St. Louis, USA), and reported as percentage. The measurement was performed in triplicate, and the average results were reported.

2.3. Branch chain length distribution

Branch chain length distribution of amylopectin between degree of polymerization (DP) 6 and 30 was determined using the fluorophore-assisted capillary electrophoresis (FACE) following the method of Srichuwong et al. (2005a). Briefly, starch was debranched with isoamylase, and the hydrolyzate was reacted with the labeling agent (APTS). The electrophoresis of the APTS-labeled hydrolyzate was conducted on the ABI PRISM 3100 Genetic Analyzer (Applied Biosystems, Foster City, CA, USA). Maltohexaose and maltoheptaose were used as references. Relative molar distribution of the branch chains between DP 6 and 30 was analyzed using the Genescan 3.7 software (Applied Biosystems). Proportional ratio of the branch chains DP 6–12 to those of DP 6–24 was determined, and designated as the amylopectin unit-chain (APC) ratio. The FACE analysis was carried out in duplicate, and the average results were reported.

2.4. Syneresis of freeze–thawed starch gels

Starch gel (5%, w/w dry basis, total weight 28 g) was prepared using a Rapid ViscoAnalyzer (Newport Scientific Ltd., Sydney, Australia). Heating and cooling were performed as follows: heating from 50 to 95 °C at 6 °C/min (after an equilibration time of 1 min at 50 °C), a holding period at 95 °C for 5 min, cooling from 95 to 50 °C at 6 °C/min and a holding phase at 50 °C for 2 min. The constant rotating speed of the paddle was 160 rpm. The resulting gel was allowed to cool at room temperature for 15 min, and the gel (5 ± 0.5 g) was transferred to a 25 ml centrifugal tube. The tube was stored at −18 °C for 21 h followed by thawing at 30 °C for 3 h in a water bath incubator. This freeze–thaw cycle (FTC) was repeated up to five times. After the 1st, 3rd and 5th FTC, five tubes were collected for determining the average syneresis. The tubes were centrifuged at 8000 × *g* for 10 min, released free water was carefully discarded, and the tube was drained on tissue paper for 10 min. Syneresis was determined as the percentage water separated to the initial gel weight.

2.5. Statistical analysis

Linear regression analysis was used to determine a relationship among variables. Prediction models were developed by multiple

Table 1
Apparent amylose content (AAC), branch chain length distribution, and APC ratio[a] of starches.

Starch sources	AAC (%)	Branch chain length distribution (%, molar basis)		APC ratio
		DP 6–12	DP 13–24	
Tubers and roots[b]				
Elephant yam	25.2	32.4	60.5	0.349
New cocoyam	22.5	34.7	58.7	0.371
Sweet potato	19.8	38.9	54.1	0.419
Kudzu	19.6	36.2	55.8	0.393
Arrowroot	20.0	31.7	58.4	0.352
Taro	16.3	36.3	57.3	0.388
Yam bean	18.4	40.8	52.1	0.439
Cassava	17.9	46.2	48.3	0.489
Potato	18.0	33.7	58.9	0.364
Edible canna	27.9	28.7	63.4	0.312
Water yam	20.8	22.8	67.5	0.253
Lesser yam	14.2	36.5	56.2	0.394
Cereals				
Corn[b]	23.4	36.5	56.7	0.392
Waxy corn	0.3	39.1	55.2	0.414
Job's tears	0.5	36.6	57.5	0.389
Indica rice	23.5	36.0	58.0	0.383
Japonica rice				
cv. Koshihikari	12.3	40.6	53.3	0.432
cv. Nipponbare[b]	13.2	42.5	52.1	0.449
cv. Hakuchomochi (waxy)	0.0	43.2	51.4	0.457
Wheat				
cv. Haruyutaka	26.9	42.8	50.4	0.459
cv. Norin61	25.1	40.3	52.3	0.435
cv. 1CW	28.2	41.2	51.4	0.445
Others				
Mung bean	30.0	36.6	55.6	0.397
Lotus root	16.0	35.2	57.8	0.378
Lotus seed	21.8	33.8	59.5	0.362
Sago[b]	21.9	37.1	56.2	0.397

[a] APC ratio (amylopectin unit-chain ratio) = DP 6–12 (%)/DP 6–24 (%).

[b] Srichuwong et al. (2005a).

linear regression (MLR) using a stepwise procedure at a 0.001 significant level. The statistical analyses were performed using the MINITAB 16.1.1 statistical software (Minitab Inc. State College, PA, USA).

3. Results and discussion

3.1. Apparent amylose content (AAC) and branch chain length distribution

Our previous studies on starches isolated from tubers, roots, seeds and stem showed that physicochemical properties of starches including gelatinization, retrogradation, swelling, pasting properties, and in vitro enzyme digestibility were correlated with branch chain length distribution of amylopectin and amylose content (Srichuwong et al., 2005a; Srichuwong, Sunarti, Mishima, Isono, Hisamatsu, 2005b; Srichuwong, Isono, Mishima, Hisamatsu, 2005). In the present study, a wider range of native starches was studied to investigate the impact of the structural features on freeze–thaw stability.

It has been known that amylose plays important roles in pasting and gelling properties, and initial gel hardness of cooked starch (Biliaderis, 2009; Jane et al., 1999; Srichuwong et al., 2005a,b). Retrograded amylose melts at between 130 and 170 °C (Biliaderis & Galloway, 1989), and is highly resistant to enzyme hydrolysis (Jane, 2009). In this study, the AAC varied between 0% and 30% for the selected starches (Table 1). The values obtained from starches isolated from mung bean, wheat, edible canna, and elephant yam were among the highest in this study (AAC > 25%). Smaller AAC of 16–24% were shown for lotus, corn, indica rice, sago, and other root and tuber starches (except for lesser yam). Lesser yam and normal japonica rice starches contained small AAC of 12–14%. Absence of amylose (0–0.5%) was observed for the starches of waxy corn, job's tears and waxy japonica rice (cv. Hakuchomochi). The variation in AAC indicated that biosynthesis of amylose varied considerably with plant genetic background.

Branch chain length distributions of amylopectin were determined, and the summarized proportions of DP 6–12 and DP 13–24 are shown in Table 1. It has been proposed that the branch chains DP 6–24 are located in a single cluster structure of amylopectin molecules, organizing semicrystalline structures of the starch granules (Hanashiro, Abe, & Hizukuri, 1996; Jane, 2009; Srichuwong & Jane, 2007). The long chains e.g., DP 13–24 would form long double helices, strengthen hydrogen bonds between chains, and span the entire length of crystalline regions. On the other hand, the existence of the short chains e.g., DP 6–12 would result in the inferior crystalline structures (Jane et al., 1999; Srichuwong et al., 2005, 2005a). Larger proportion of these short chains has been reported in relation to decreased gelatinization temperatures and swelling power, and increased in vitro enzyme digestibility of starch granules (Edwards et al., 1999; Jane et al., 1999; Jobling et al., 2002; Nakamura et al., 2002; Noda et al., 1998; Srichuwong et al., 2005, 2005a, 2005b). In this study, APC ratio was determined to represent a distribution of short chains DP 6–12 in the crystalline regions of starch granules. As shown in Table 1, the APC ratios ranged between 0.253 and 0.489 among the selected starches. Water yam and edible canna starches showed small values of APC ratio of 0.253 and 0.312, respectively, implying a minor contribution of short branch chains in their semicrystalline structures. In contrast, the short chains DP 6–12 would be largely located in the semicrystalline structures of japonica rice, wheat, yam bean, and cassava starches according to their APC ratios (0.432–0.489) which were among the highest. During long term storage of cooked starches, the short chains DP 6–12 have been reported to delay retrogradation of amylopectin as deter-

Table 2
Syneresis (%) of starch gels after the 1st, 3rd, and 5th freeze–thaw cycle (FTC).

Starch sources	Syneresis (%)		
	1st FTC	3rd FTC	5th FTC
Tubers and roots			
Elephant yam	67.9 ± 0.6	75.5 ± 1.3	77.3 ± 0.7
New cocoyam	62.1 ± 1.5	71.9 ± 1.6	74.4 ± 3.5
Sweet potato	28.4 ± 0.7	69.0 ± 1.4	74.0 ± 2.8
Kudzu	24.2 ± 2.2	63.5 ± 2.1	74.6 ± 3.7
Arrowroot	43.4 ± 3.1	65.1 ± 1.1	66.5 ± 1.6
Taro	20.7 ± 0.1	56.7 ± 0.2	67.2 ± 1.2
Yam bean	8.9 ± 3.2	48.6 ± 3.2	63.7 ± 1.7
Cassava	nd[a]	38.9 ± 0.7	51.5 ± 2.5
Potato	60.0 ± 1.7	71.5 ± 2.8	75.6 ± 4.1
Edible canna	73.5 ± 3.6	74.7 ± 2.4	74.9 ± 1.2
Water yam	67.0 ± 1.5	73.6 ± 0.8	78.7 ± 3.7
Lesser yam	28.4 ± 2.3	67.4 ± 1.5	69.5 ± 1.5
Cereals			
Corn	35.4 ± 1.9	69.5 ± 0.7	73.3 ± 2.4
Waxy corn	9.6 ± 1.1	33.7 ± 2.1	53.9 ± 1.0
Job's tears	4.2 ± 3.1	25.9 ± 3.3	46.5 ± 0.7
Indica rice	45.7 ± 2.6	69.6 ± 3.7	74.9 ± 3.2
Japonica rice			
cv. Koshihikari	nd	nd	7.3 ± 0.8
cv. Nipponbare	nd	nd	15.9 ± 3.5
cv. Hakuchomochi (waxy)	nd	nd	nd
Wheat			
cv. Haruyutaka	58.2 ± 1.4	60.2 ± 1.7	63.1 ± 3.8
cv. Norin61	51.9 ± 1.1	62.8 ± 3.3	67.5 ± 2.9
cv. 1CW	55.8 ± 0.4	58.7 ± 4.2	64.3 ± 0.4
Others			
Mung bean	42.8 ± 0.7	64.5 ± 2.5	73.1 ± 0.9
Lotus root	35.1 ± 2.5	64.6 ± 3.8	71.2 ± 0.2
Lotus seed	52.6 ± 2.6	62.4 ± 1.9	65.2 ± 3.5
Sago	21.7 ± 3.4	66.8 ± 0.4	68.8 ± 0.6

[a] Not detected.

Table 3
Optimal multiple linear regression models to predict the relationship between syneresis (%) and structural features of starches ($n = 26$, $P < 0.001$).

Model	Coefficient	*P* value	R^2
Syneresis (%), 1st FTC			
Intercept	93.2	0.001	0.75
AAC	1.8	0.001	
APC ratio	−233.0	0.001	
Syneresis (%), 3rd FTC			
Intercept	100.4	0.001	0.67
AAC	1.8	0.001	
APC ratio	−199.0	0.002	
Syneresis (%), 5th FTC			
Intercept	103.8	0.001	0.57
AAC	1.4	0.001	
APC ratio	−175.6	0.008	

mined by differential scanning calorimetry (Kalichevsky, Orford, & Ring, 1990; Shi & Seib, 1995; Srichuwong et al., 2005a). Nevertheless, the relationship between the branch chain length and syneresis of starch gels has not been established, especially with a wide variety of starches.

3.2. Syneresis of freeze–thawed starch gels

Freeze–thaw stability of starch gel, measured as % syneresis, was determined after the 1st, 3rd and 5th FTC, and shown in Table 2. Release of free water was not observed in any of the freshly prepared gel prior to the treatment. In general, the syneresis increased with an increase in number of FTC, and varied with the botanical sources. With increase in the number of FTC, the extent of phase separation would be accelerated by starch retrogradation.

Among the starches tested, the starch gels of elephant yam, new cocoyam, potato, edible canna, and water yam rapidly lost their stability after the 1st FTC where the syneresis degrees were larger than 60% (Table 2). Subsequent FTC slightly increased their syneresis levels, achieving 74–79% after the 5th cycle. Similarly, high syneresis degrees of 52–58% after the 1st cycle were observed for lotus seed and wheat starch gels. Syneresis of these starches increased slightly after the subsequent FTC, achieving 63–68% after the 5th cycle. Smaller syneresis after the 1st FTC (20–46%) were shown for many starches including sweet potato, kudzu, arrowroot, taro, lesser yam, corn, indica rice, mung bean, lotus root, and sago. However, their syneresis increased to 57–70% after the 3rd cycle, and reached 67–75% after the 5th cycle. After the 1st FTC, a very small syneresis of 9% were observed for yam bean starch gel; however the syneresis greatly increased to 49% and 64% after the 3rd and 5th cycle, respectively. Similarly, cassava starch gel showed a good stability after the 1st FTC as no syneresis occurred, however the gel lost its stability after the subsequent FTC, achieving the syneresis of 39% and 52% after the 3rd and 5th FTC, respectively. Among the normal starches tested, only the starch gels of japonica rice exhibited no syneresis up to three FTC, and reached 7–16% after the 5th cycle. In spite of the absence of amylose, syneresis occurred for waxy corn and job's tear starch gels, which were 4–10%, 26–34% and 47–54% after the 1st, 3rd, and 5th FTC, respectively. In this study, waxy japonica rice was the most stable gel because no syneresis was observed after the 5th FTC. Accordingly, our findings provided comparative guideline on syneresis potentials of these native starches which would be considered as the "clean-label" ingredients for frozen food application.

3.3. Relationship between syneresis and structural features of native starches

As shown in Table 2, the gels prepared from japonica rice starches including normal and waxy types were more resistant to syneresis than the others. It was noted that these starches had relatively high APC ratio (0.432–0.457) and small AAC (0–13%) (Table 1). Comparing with the japonica rice, the starch gels of yam bean, cassava, and wheat, possessing comparable APC ratios (0.435–0.489) but larger AAC (18–28%), exhibited more syneresis. Other starches having smaller values of APC ratio tended to be highly prone to syneresis. Linear regression analyses using a single variable showed that the syneresis degrees at the 1st, 3rd, and 5th FTC were positively correlated with the AAC ($R^2 = 0.53$, 0.51 and 0.41, respectively, $P < 0.001$) and negatively correlated with the APC ratio ($R^2 = 0.39$, 0.32, and 0.28, respectively, $P < 0.005$). The greater coefficient of determination (R^2) shown for AAC might indicate a greater contribution of amylose retrogradation to syneresis, which would be attributed to the long linear chain and high mobility of amylose molecules. On the other hand, amylopectin with its higher water holding capacity, highly branched structure and shorter chains would retrograde in a slower rate (Biliaderis, 2009; Srichuwong & Jane, 2007).

Because no significant correlation between AAC and APC ratio was observed ($R^2 = 0.05$, $P = 0.266$), both variables would contribute differently to the syneresis. In order to understand the unit-effect of AAC and APC ratio on freeze–thaw stability as a whole system, the multiple linear regression (MLR) models were generated to predict their contribution to syneresis (Table 3). When both AAC and APC ratio were selected as predictors, the prediction models constructed for syneresis at the 1st, 3rd, and 5th FTC were obtained at the 0.001 significant level ($R^2 = 0.75$, 0.67 and 0.57, respectively). The R^2 values representing a measure of the global fit of the model were higher than the values analyzed from the single variable. These results confirmed that syneresis tendency of native starch gels was reduced with a combination of smaller amylose content and greater proportion of amylopectin branch chains DP 6–12. The model for syneresis at the 1st FTC accounted for more proportion of variability in syneresis (75%) than those obtained from the 3rd and 5th FTC (67% and 57%, respectively). On the basis of the proposed models, the syneresis of starch gels would increase by an average factor of 1.8%, 1.8%, and 1.4% after the 1st, 3rd, and 5th FTC, respectively, if the AAC increased by 1%, while the APC ratio remained unchanged. Similarly, a 1% increase in proportion of the short amylopectin chains DP 6–12 (as an increase in 0.01 of APC ratio) with AAC held fixed would decrease the syneresis by an average factor of 2.3%, 2.0%, and 1.8% after the 1st, 3rd, and 5th FTC, respectively. Accordingly, the MLR using AAC and APC ratio as the predictors would be a useful tool for predicting the freeze–thaw stability of native starch gels.

In addition to the structural features, a presence of non-carbohydrate components such as phospholipids in normal cereal starches could also influence syneresis. It is known that normal wheat and indica rice starches contain larger amounts of phospholipids in comparison to other starches (Kasemsuwan & Jane, 1996; Singh, Singh, Kaur, Sodhi, & Gill, 2003). The phospholipids have a tendency to form helical complexes with amylose during starch gelatinization. The complexes restrict granular swelling, maintain integrity of swollen granules, and result in a stiff gel (Jane et al., 1999; Jane, 2009; Srichuwong et al., 2005b; Tester & Morrison, 1990). Accordingly, the closely located starch molecules resulted from the limited swelling might accelerate retrogradation, and, eventually, syneresis of starch gels. This phenomenon might contribute, to some extent, to the high syneresis levels of wheat starch gels (Table 2). A study on nineteen indica rice starches also found a significant negative correlation between swelling power and syneresis, but no correlation was observed between amylose content and syneresis (Singh et al., 2006).

4. Conclusion

Overall, our findings demonstrated that syneresis of starch gels largely depended on botanical sources, which were attributed to their differences in structural features. Syneresis occurred very slowly for normal and waxy japonica rice starches. In contrast, some tuber and root starches such as elephant yam, new cocoyam, potato, edible canna and water yam were highly prone to syneresis. This instability would limit their use in frozen food applications. The individual effects of amylose content and branch chain length distribution of amylopectin on syneresis up to five FTC were demonstrated, and the prediction models for syneresis were proposed. Both factors showed substantial contributions to syneresis of starch gels. Accordingly, freeze–thaw stability of native starches would be predicted from their structural features.

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