Starch gel foods in cookery science: application of native starch and modified starches

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Abstract This paper reviews starch gel foods from the perspective of cookery science: *warabi mochi* (traditional sweet gel in Japan) and blancmange as hard gels and pastry cream/custard as a soft gel. Since *warabi mochi* is made from expensive *warabi* starch, physicochemical properties of several starches were tested as possible replacers. High potential of sago starch as a replacer was demonstrated as compared with sweet potato, potato, tapioca, and kudzu starches which are currently used as the replacers. Sago starch showed excellent characteristics in gel elasticity comparable to sweet potato and potato starches, high gel cohesiveness and low gel adhesiveness comparable to tapioca starch, and gel hardness comparable to kudzu starch. Toward quality improvements of *warabi mochi*, its preparation methods were also optimized. For instance, trehalose was added to suppress starch retrogradation in *warabi mochi*, and modified wheat starch was added to stabilize its gel quality. Meanwhile, *warabi mochi* is primarily a mixture of starches, sugars, and water, whereas most starch gel foods are mixtures of the primary ingredients and secondary ingredients such as proteins and fats. As for the blancmange, milk was replaced with soy protein isolate or soy milk powder for its quality improvement. For maximizing the physicochemical properties as well as taste, ratio of starch, protein, and fat was optimized by Scheffé's simplex lattice design method: its triangular diagram clearly showed its optimal ratio for blancmange of high quality. Regarding pastry cream/custard, since its melting mouthfeel governs overall quality preference, methods to evaluate the melting mouthfeel were established. Thereafter, applicability of modified starches to pastry cream/custard was investigated to fit its texture to each food preparation. Based on physicochemical properties of the modified starches, pastry cream/custard preparation was adjusted to each of various food products.

Keywords starch, gel, retrogradation, *warabi mochi*, blancmange, pastry cream/custard

1. Introduction

Starch extracted and purified from various plants are used in cooking and processing of foods. Starch can be divided into two categories: starches from cereals and seeds grown in relatively dry areas and those from roots and tubers grown in relatively wet areas [1]. Environmental factors like soil and climate for a plant may affect physicochemical properties of the starch from the plant: particle size, amylose content, amylopectin chain length distribution, solubility, swelling power, gel transparency, and gelatinization and retrogradation temperatures [1]. When heated in water, starch particles swell with amylose molecules partly eluted, resulting in gelatinization into starch paste [2–4]. When the paste is cooled, it goes through a process known as retrogradation where gelatinized starch molecules recrystallize and the paste transforms from sol to gel depending on its starch content [2–4].

Starch gels have been intensively studied [5–12], and their applications to cooking have been studied from the perspective of cookery science in terms of starch types [13], cooking temperatures [11, 14–29], addition of various sugars as primary constituents [30, 31], and addition of secondary ingredients such as proteins and fats [32–39]. As for quality improvements of starch gels, physicochemical properties of starch gels have been investigated toward applications of native and modified starches for cooking and/or processing starch gel foods such as *warabi mochi* (traditional sweet gel) [40–45], blancmange [34–38], and pastry cream/custard [46].

Physicochemical and rheological properties of starch gels depend not only on properties of starch as a primary

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constituent but also on methods of preparation such as starch concentration, heating and cooling conditions, and secondary constituents (e.g., sugars, proteins, and fats). Above all, starch gel properties are highly affected by the processes of gelatinization and/or retrogradation [13]. Starch suspension can be gelatinized by heating, transforming into sticky and translucent paste. Retrogradation hardens the gels and makes them cloudy [13], while the amount of water leakage from the gels increases due to enhanced syneresis [13]. Native starches can be processed into chemically, physically, and/or enzymatically modified starches [47]. Modified starches showing lowered gelatinization temperature, improved texture, and resistance to refrigeration and/or freezing [41–44] are commonly used in the production of starch gel foods such as blancmange and pastry cream/custard. Furthermore, modified starches [48] as well as sugar [49–51] can be added to suppress unfavored retrogradation in starch gel foods. However, most of the reports on Japanese starch gel foods are only available in Japanese [41–46, 53–59].

Sago is still an untapped source of starch [41, 42] and the development of further applications are expected in the food industry [41, 42]. Sago palm (*Metroxylon sagu* Rottb.) is originated in the area between the Moluccas in eastern Indonesia and New Guinea. Its cultivation area includes swampy tropical areas and drylands and currently expands in Southeast Asia and Oceania [52]. In Japan, sago starch is imported from Malaysia and Indonesia as a modified starch for dusting noodles [41, 42]. Sago starch and its gels show unique physicochemical and rheological properties as compared with other starches including modified tapioca (cassava) and wheat starches [41–46, 53–59], and it is expected that sago starch should have a potential to be used in cooking/processing starch gel foods. However, most of the studies on the applications of sago starch are described in Japanese [46, 48–58].

Since studies on starch gel foods, particularly on *warabi mochi*, have been primarily reported in Japanese and that there are potential demands to refer to the important data in the reports, this paper reviews those reports in Japanese on the applications of native/modified starches including sago starch.

2. Warabi mochi

Warabi mochi [40, 60] is a Japanese sweet gel that is originally made from rhizome starch of bracken (*Pteridium aquilinum* Kuhn; *warabi* in Japanese). *Mochi*, a sticky food generally made with glutinous rice or waxy starch, is categorized into *Tsuki-mochi* and *Kone-mochi*. *Tsuki-mochi* is a rice cake made by pounding steamed glutinous rice. *Kone-mochi* is a starchy gel which is made by stir-heating or steam-heating a mixture of water and starch or cereal grain powder. *Warabi mochi* is a *Kone-mochi*. Although it is not

made from glutinous rice or other waxy starches, it is called “*mochi*” for its sticky texture. *Warabi mochi* is prepared by stir-heating a mixture of water and *warabi* starch approximately at starch content of 15–16% [60]. For processing *warabi mochi*, sugar is often added for preference and shelf life. The suspension is cooled to form a gel, and the gel is usually served cold with toasted soybean flour and brown sugar syrup toppings. Since *warabi* starch is not highly purified, it is slightly colored brown and thus *warabi mochi* is a translucent brown gel. Its characteristic appearance and texture are favored as a traditional dessert in Japan. However, it is currently very difficult to use *warabi* starch for *warabi mochi* since the availability is limited at high price. *Warabi* starch is sold at a price of JPY 12,000–15,000 (USD 116–145)/kg, and it is 30–35 times more expensive than sweet potato or tapioca starch and 20–24 times more expensive than sago starch. Kudzu starch, another traditional starch in Japan as a replacer for *warabi* starch, is also expensive: approximately JPY 8,500 (USD 82)/kg. Therefore, two categories of *warabi mochi* are commercially available in Japan: expensive traditional *warabi mochi* made from *warabi* starch and a novel type available at reasonable price made from substitutes of *warabi* starch such as sweet potato starch and modified or unmodified tapioca starch. Novel *warabi mochi* requires in its quality low syneresis, high translucency, shape retainability, and texture relevant to those of its conventional product.

Sensory evaluation (Fig. 1) revealed that novel *warabi mochi* made from sago starch was comparable to the traditional type in terms of color, smoothness on cutting, hardness, and bite feel [44]. Preference tests showed a tendency where novel *warabi mochi* was rated higher than traditional one in appearance and texture (data not shown). Based on the high performance of sago starch as a replacer of *warabi* starch for *warabi mochi*, physicochemical properties of sago starch gel have been studied intensively toward its optimal applications to starch food gels including *warabi mochi*.

2-1. Physical properties of native starches and their gels [14, 41–45]

In the cooking process, the physical properties of native starches and their gels should be considered for serving good dishes of starchy foods. In this section, the relevance of the physical properties of native starches and those of their gels is reviewed as compared with those of sago starch and its gels which are judged important for processing/cooking novel *warabi mochi* as described in the previous section.

In general, starches with higher amylose contents form gels faster [61]. Starches of higher apparent amylose contents [62] such as wheat (24.6%), sago (24.5%), and corn (24.5%) starches retrograded faster than starches from kudzu (21.8%), *warabi* (21.0%), potato (19.7%), sweet

Fig. 1 Sensory evaluation of *warabi mochi* samples using conventional (warabi) and novel (sago) starches. *significant difference at $p < 0.05$. **significant difference at $p < 0.01$. —○—: sago starch; —●—: warabi starch

potato (19.7%), tapioca (17.8%), and rice (15.0%). Amylopectin chain length distribution was analyzed by gel filtration method [63], and the amount ratio of its eluted chain fractions (Fr. III/Fr. II) was used to find out the relevance between the distribution and mechanical properties of the starch gels. Mung bean, sago, and sweet potato starches showed amylose contents (Fr. I) of 30.8, 25.9, and 19.1% as well as comparable Fr.III/Fr.II at 2.5, 2.4, and 2.1, respectively. Mechanical properties of their gels were also comparable [64]. Gelation behaviors of several starches were evaluated by using Rapid Visco Analyzer (RVA) [65], and sweet potato, tapioca, and sago starches showed similar viscosity behaviors upon heating in water [64]. After preparing starch gels at a starch content of 7.5% (w/w) by using the RVA with subsequent refrigeration (5°C for 2 h), textural profile analysis (TPA) was carried out to evaluate their mechanical properties (Fig. 2). Potato, sago, and kudzu starch gels were hard, whereas rice and tapioca starch gels were soft. The adhesiveness parameters of sago, rice, and tapioca starch gels were low, and sago and rice starch gels were highly cohesive. Static viscoelasticity measurement showed retarded elastic deformations and long retardation times of potato and sago starch gels compared to corn starch gel, indicating high performance of potato and sago starches for gel formation. Loss tangent ($\tan \delta$) was evaluated as a dynamic viscoelasticity parameter [66] for sago, sweet potato, potato, and corn starches as 0.7, 0.5, 0.42, and 0.02, respectively. The highest $\tan \delta$ for sago starch indicated the highest contribution of viscosity

to viscoelasticity among the gels, indicating the most favorable texture for *warabi mochi* [44]. Furthermore, as for unfavorable syneresis during refrigerated storage, losses of water from potato and sago starch gels were favorably low at 10.0% (w/w) and 2.2% (w/w), whereas those of mung bean and corn starch gels were high at 30.3% (w/w) and 25.2% (w/w), respectively [14].

It can be summarized that sago starch was found to have good features similar to corn starch for the amylose content and to sweet potato for the amylopectin chain length distribution and gelation behavior upon heating. Sago starch gel showed comparable characteristics for hardness of kudzu starch gel, viscoelasticity of potato or sweet potato starch gel, and high cohesiveness, low adhesiveness, and low syneresis of tapioca starch gel. Therefore, sago starch was found suitable for replacing expensive warabi starch in processing/cooking *warabi mochi*, and it was also indicated that sago starch was even better than warabi starch.

Since high potential abilities of sago starch as a starch replacer for novel *warabi mochi* were revealed, its applicability was further studied in comparison with corn starch that shows comparable amylose contents [14] as a representative of cereal starches as well as potato starch whose average granular size [14] and low water loss [14] are comparable as a representative of tuber starches. Other starches were also compared with sago starch as necessary.

Fig. 2 Textural properties of various starch gels. Tapioca starch gel was stored for 24 h at 5°C before the measurements, while other starch gels were stored for 2 h at 5°C. Each letter (a to e) shows a significant difference in the level of each parameter ($p < 0.05$).

2-2. Suppression of retrogradation in the process of freezing and thawing

Assuming that novel *warabi mochi* could be frozen at home and factories and thereafter thawed upon serving and delivery, the effect of freezing and thawing on the quality of novel *warabi mochi* made from sago starch, was investigated. In addition, it was also assumed that the process of freezing and thawing could be repeated, particularly at home.

Repeated freezing and thawing accelerates the retrogradation process of starch gels, and the quality of starch gels decreases [67]. Since sugars are often added to *warabi mochi* for suppressing its retrogradation as well as supplementing sweetness [67], sucrose and trehalose were added to novel *warabi mochi* to evaluate the suppression of retrogradation in the process of freezing and thawing. Novel *warabi mochi* was prepared using sago starch as well as corn, potato, and sweet potato starches. Starch gels containing 11% (w/v) starch and 30% (w/w) sugar were applied to the processes of freezing (−20°C for 22 h) and thawing (ambient temperature for 2 h), which was also repeated 3, 5, and 7 times. The process leads to recrystallization of starch molecules in gelatinized starch and thus hardens the

gel accompanying water loss [68]. Therefore, water loss (Fig. 3) and gel hardness (Fig. 4) were evaluated as indices for quality loss after the repeated process as well as sensory test to evaluate quality attributes and preference of the processed gel.

Water loss due to the process of freezing and thawing was reduced by adding sucrose or trehalose to each starch gel (Fig. 3). Trehalose was more effective than sucrose in each case. Water loss from sago starch gel was more suppressed by addition of trehalose than potato, sweet potato, and corn starches, up to 3 cycles of freezing and thawing process.

Since the sensory evaluation of the gels revealed a high preference for sago and potato starch gels, the effect of the process on the gel hardness was further investigated using the gels (Fig. 4). Sucrose or trehalose addition suppressed the hardening of the gels of sago and potato starches, while the gels without the sugars became hard after the process of freezing and thawing. In addition, sago starch gel with sucrose or trehalose added showed more suppressed hardening than potato starch gel. Whiteness was suppressed by the addition of either sucrose or trehalose, and trehalose suppressed the whitening of sago starch gel more than sucrose [31].

Fig. 3 Influences of freezing-thawing cycles on water loss of starch gels. □: control; ■: sucrose; ▨: trehalose

Fig. 4 Effect of sucrose or trehalose addition on the hardness of starch gel. ●: sago starch; ●- - : sago starch + sucrose; ○ · · : sago starch + trehalose; ■- - : potato starch; ■- - : potato starch + sucrose; □ · · : potato starch + trehalose

Novel *warabi mochi* was prepared using several starches at a starch content of 15% with/without sucrose or trehalose added, and the gel was applied to sensory evaluation after the process of freezing and thawing. As for the gel with sucrose added, starch gel of sago was the best and that of potato followed among the tested starch gels. Sago starch gel with trehalose added was preferred to potato starch in terms of translucency. The novel *warabi mochi* from sago starch was significantly more preferred than that from potato starch even after 3 cycles of freezing and thawing in terms of sweetness, hardness, bite feel, stickiness, and total score.

2-3. Cooking procedure for the novel *warabi mochi*

Warabi mochi is often prepared by stirring the materials upon heating, while it can sometimes be prepared in a shorter time by stand-steaming the mixture after heating to quasi-gel. The effect of preparation methods, stir-heating and stand-heating, on the gel properties were compared with gels (15% (w/w) starch content) using sago, potato, corn, tapioca, and modified starches without any sugar supplementation. After the freezing-thawing process, quality of the gels was evaluated by hardness, water loss, and sensory test.

Gel hardness measured after 2 h storage at ambient temperature was almost comparable among all the tested gels, but difference in the hardness tended to expand after cycles of freezing and thawing the gels. The stand-heating method showed a slightly higher tendency in the hardness.

Water loss also tended to be slightly higher for the gels prepared by stand heating. The homogeneous gels produced by stir heating seemed to have retrograded less, resulting in less hardness (Fig. 5) and less water loss [57].

In both cases, corn starch gave the highest gel hardness followed by sago, potato, and tapioca starches in this order. As for the gels from modified starch (hydroxypropylated wheat starch), increase in the hardness was extremely low (Fig. 5) and water loss was low as well (data not shown) even after 10 cycles of the process.

Since sago and potato starch gels were highly preferred among tested gels as described above, the effect of preparation methods on the sensory qualities of the gels was studied. Stir-heated sago starch gel was preferred in terms of hardness, elasticity, stickiness, and total score. On the other hand, stand-heated potato starch was preferred in terms of hardness, elasticity, and stickiness. It was suggested that preparation methods for starch gel should depend on the starch variety.

2-4. Modified starch as an additive for improved stability of starch gels

Starch gel consisting solely of modified starch (hydroxypropylated wheat starch) showed extremely high stability against the process of freezing and thawing (Fig. 5) [57]. It can be speculated that the hydroxypropyl moiety of the modified starch molecules may retard starch retrogradation via steric hindrance. Despite the high processing stability, sensory quality of the modified starch gel was low [57], so it was used as an additive to improve gel stability. Starch

Fig. 5 Influences of freezing-thawing cycles on hardness of starch gels. —●—: sago starch; —▲—: corn starch; —○—: potato starch; —■—: tapioca starch; —△—: hydroxypropylated wheat starch

gel was prepared by using mixtures of native starch (80%) and the modified starch (20%), and the gel quality after the process of freezing and thawing was evaluated by hardness, water loss, whiteness, and sensory attributes.

When modified starch (hydroxypropylated wheat starch) was added to native starch, the gels of sago, potato, and corn starches became more resistant to all the processes of freezing and thawing, showing less increases in hardness and water loss than those without addition of the modified starch (Fig. 6). Tapioca starch gel showed slower increase in hardness and slower increase in water loss with freezing-thawing cycles than other native starches. Among the gels of starches and starch mixtures, the mixture of sago and modified starches showed the best resistance to the process. Reduced whitening was observed in the gels of mixtures containing sago or potato starch and the modified starch even after 1 day storage at 5°C, suggesting possible replacement of native starch by 20% w/w with the modified starch for increased stability against the cycled process of freezing and thawing.

Traditional *warabi mochi* is better suited to be cooked in the kitchen and consumed within a short time. In commercial products sugars can be added to traditional *warabi mochi* to suppress retrogradation. On the other hand, novel *warabi mochi* are commercially made from nonconventional starches such as sweet potato and tapioca starches. The addition of trehalose and/or modified starch for suppressing retrogradation would also be advantageous for the commercial products to be stored under refrigeration and/or freezing.

3. Blancmange

Blancmange is a sweet dessert and it literally means “white food”. It is often prepared by mixing corn starch as a thickener with sugar and milk/cream with subsequent gelatinization and cooling [69]. A good blancmange with less stickiness can be prepared by stir-heating the mixture after boiling [32]. Sago starch was revealed to have high potential properties to replace other starches [41, 42]. Furthermore, milk can be replaced with soy protein isolate (SPI) and soy milk powder (SMP) which are expected to contribute to human health via lowering blood cholesterol level [70, 71] and reducing hyperlipidemia [70, 71]. Sago starch with comparable amylose contents to corn starch forms good gel [41, 42], and the gel is more elastic than that of potato starch [44]. Therefore, the applicability of sago starch in cooking blancmange was tested in comparison with corn and potato starches. The effect of milk substitutes on the blancmange quality was studied as well.

3-1. Effect of milk substitutes on blancmange quality

The physicochemical properties of the novel blancmange in which the milk was replaced with SPI (SPI blancmange) or SMP (SMP blancmange) were compared with a conventional blancmange which was prepared using corn starch, water, and milk. SPI was composed of 92% protein and <1% fat and SMP contained 50% protein and 17% fat. hardness, adhesiveness, elasticity, and formability was reduced in SPI blancmange, and the reductions were further enhanced in SMP blancmange. Sensory tests revealed that SPI blancmange was preferred in terms of appearance, color, and elasticity while SMP blancmange was evaluated

Fig. 6 Effect of HPW starch addition and freezing-thawing cycles on gel hardness and water loss. —●—: sago starch; —▲—: corn starch; —○—: potato starch; —■—: tapioca starch; —△—: HPW; ---●---: sago starch + HPW; ---▲---: corn starch + HPW; ---○---: potato starch + HPW; ---■---: tapioca starch + HPW (HPW: hydroxypropylated wheat starch). Gels were prepared by using RVA.

as a good gel with good flavor and smooth texture. It was suggested that milk can be replaced with SPI or SMP in novel blancmange with high preferences [34].

3-2. Optimization of a mixing ratio of starch, SPI, and soybean oil for novel blancmange

It was shown that various types of novel blancmange could be prepared by replacing milk with SPI or SMP which has different protein and fat contents from milk. Therefore, the effect of starch, protein, (SPI) and fat (soybean oil) contents on the quality of blancmange was investigated by applying Scheffé's simplex lattice design method [36]. The method [72] enables to optimize an experimental design with a minimum number of trials consisting of more than 2 components and to visualize the relationship between food quality and composition depicted as an estimation

curve in a diagram.

The corners X_1 , X_2 , and X_3 denote composition ratios for maximum amount of starch (corn starch or sago starch), SPI, and soybean oil, respectively. The triangular diagram depicts 10 lattice points where gel can be formed for measuring mechanical parameters. Table 1 shows the lattice point and mixing ratio for each analysis sample. Gel samples were prepared based on Table 1, and its viscosity, hardness, and gel shape retention were evaluated. Based on the data, estimation curves were drawn on each diagram of the measured parameter. Details of the method are described elsewhere [36, 37, 72].

Blancmange samples based on sago and corn starches mostly resulted in similar estimation curves among tested parameters. However, differences were observed between the starches in gel shape retainability and adhesiveness. Comparison of gel shape retainability of blancmanges from sago and corn starches are shown in Fig. 7 [36]. Smaller figure in the triangular diagrams indicates better shape retainability. For sago starch blancmange, smaller SPI ratio resulted in smaller figure, indicating negative contribution of SPI to the shape retainability. For corn starch blancmange, the highest starch ratio (sample identification (ID) number ①) gave the highest gel shape retainability [36].

Blancmange composed of sago starch, water, and SPI with sugar added was also analyzed in the same manner as in Fig. 7 by the simplex lattice design method [34]. The gel samples with high starch ratios showed high hardness, high elasticity, and reduced water loss [34]. The positive contribution of high starch ratio to the gel hardness agreed with the trends in the gels composed of starch, sucrose, and milk as analyzed by the simplex lattice design method [37]. Starch is a major player to harden starch gels as mixtures. In addition, scanning electron microphotographs indicated fine structures of the gel network [37], suggesting possible contribution of the network to the gel properties.

Table 1 Lattice point and its corresponding composition on Scheffé's simplex lattice design

sample ID number	lattice point (X_1, X_2, X_3)	ingredients (g/100 ml H_2O)		
		starch	soybean protein isolate	soybean oil
①	(1, 0, 0)	13	4	3
②	(0, 1, 0)	7	10	3
③	(0, 0, 1)	7	4	9
④	(1/2, 1/2, 0)	10	7	3
⑤	(0, 1/2, 1/2)	7	7	6
⑥	(1/2, 0, 1/2)	10	4	6
⑦	(1/3, 1/3, 1/3)	9	6	5
⑧	(2/3, 1/6, 1/6)	11	5	4
⑨	(1/6, 2/3, 1/6)	8	8	5
⑩	(1/6, 1/6, 2/3)	8	5	7

Fig. 7 Estimation curves of the shape-retaining property of the starch, soybean protein and soybean oil mixture gel. ①~⑩: sample number (Table 1), Bold characters indicate the mold-retaining property (%). The smaller the number in the figure, the better the mold-retention ratio.

Major players in physicochemical and/or mechanical properties of starch gel foods can be identified by the simplex lattice design method. We showed that the mechanical parameter of corn starch blancmange can be mimicked by applying the method to design sago starch blancmange [36]. The method can further be applied to other starch gel foods.

4. Pastry cream/custard

Pastry cream or custard is a weak starch gel used for cream puff, cream bread/bun, pie filling, and so forth. It is prepared by mixing whole egg, milk, sugar, and corn starch or wheat flour (cake flour), and the final starch content ranges 3–5% w/w [46]. As a bread/bun filling, stretching smoothness and cohesiveness are required, while gel shape retainability is requested as a pie filling for a good appearance of the cross-section when cut with a knife.

In the commercial applications of pastry cream, modified starches are often added to suppress retrogradation and/or to improve the texture, both of which can be worsened by refrigeration storage. Two types of modified tapioca starches, distarch phosphate (P) and acetylated distarch phosphate (AP), have been developed, and the modified starches were further modified enzymatically by using α -amylase from *Aspergillus niger* (P + E and AP + E) [2, 43]. The modified starches offer their gels increased stretchiness and hardness and they can form gels with high springiness and shape retainability [2, 73]. The modified starches (P, AP, P + E, and AP + E) were applied to improve physicochemical properties of pastry cream/custard. Since it had been identified that melting mouthfeel was a key for the texture evaluation of pastry cream/custard, methods to evaluate “melting mouthfeel” by mechanical measurements were investigated [46].

4-1. Characterization of several modified starches

Physicochemical properties of the modified starches have been investigated to select suitable starches for pastry cream/custard as compared with those of tapioca, corn, and wheat starches which have been typically applied to the foods as well as wheat flour (cake flour) [46].

Apparent amylose contents measured by iodine amperometric titration were 18.1% for native tapioca starch and 18.6–20.0% for the modified starches (A, P, A + E, and AP + E) [46]. The swelling power and solubility of the four modified starches at 70–90°C were lower than native tapioca starch. They were lower with higher degree of cross-linking [46]. Differential scanning calorimetry (DSC) [74] revealed that onset, peak, and conclusion temperatures upon gelatinization were higher for modified starches P and P + E (hereafter, Group P starches) than those of AP and AP + E (hereafter, Group AP starches). Group P starches showed similar specific temperatures to those of native tapioca and

corn starches. The gelatinization properties of Group AP starches were similar to wheat flour and wheat starch. Pasting temperatures of the modified starches measured by RVA were lower than that of native tapioca starch, and the maximum viscosity was higher and the break down was smaller, suggesting that the modified starch was thermally stable as compared with its native counterpart. Moreover, the final viscosity (measured after cooling to 50°C) was higher and the setback was larger than native starch. It was suggested the modified starches would retain the shape of the gels better than the native tapioca starch.

Starch gels were prepared by using the modified starches at a starch content of 7.5% and stored at 5°C for 2 h. Thereafter, texture properties of the gels were evaluated as shown in Fig. 8. Corn starch gel was the hardest, followed by the gels of Group P starches. The gels of Group AP starches were softer than those of Group P starches, tapioca starch or wheat flour. Gels from the modified starches showed higher values in adhesiveness than tapioca starch gel. The gels of Group P starches particularly showed higher adhesiveness than corn starch gel. The gels of Group AP starches were highly cohesive. Cohesiveness was lower with the gel of P + E starch than that of P starch. Since physicochemical properties of modified starches largely depend on their modification methods, optimal modified starches should be applied to produce/cook pastry cream/custard [46].

4-2. Texture of pastry cream/custard with modified starches

Modified tapioca starch gels (P, AP, P + E, and AP + E) were used to study the texture of pastry cream/custard. RVA measurements revealed that the effect of sugar addition (18.2% w/w) to the system on the pasting behavior was relatively small. As for the TPA, sugar addition showed a slight tendency for reduced hardness and adhesiveness with cohesiveness increased. However, it was indicated that sugar addition would not affect the TPA properties of modified starch gels drastically.

Pastry cream/custard was prepared using the modified starches. TPA indicated that texture of the products was almost comparable among those prepared using wheat flour, corn starch, and the modified starches, indicating no obvious relevance in texture between starch gel and pastry cream/custard [46]. It was speculated that starch at low content in pastry cream/custard did not contribute to the texture much or that TPA was not able to detect the subtle differences in the texture.

Therefore, sensory evaluation was carried out to supplement the mechanical measurements. Pastry cream/custard of which wheat flour was by 10% replaced with the modified starch P + E was highly preferred due to its good melting mouthfeel among the samples tested [46]. It was indicated that partial replacement of wheat flour with modified tapioca starch would be a good alternative to produce/cook pastry cream/custard.

Fig. 8 Textural properties of gels made from wheat flour and corn, tapioca, and modified tapioca starches. Each letter (a to e) shows a significant difference in the level of each parameter ($p < 0.05$).

4-3. Method to evaluate “melting mouthfeel” for texture of pastry cream/custard

Since there was no quantitative method to evaluate melting mouthfeel of pastry cream/custard, several viscoelastic measurements were carried out and the relationship between the measured parameters and sensory results was analyzed.

TPA measurements did not show any relevance between measured parameters and sensory attributes specific to melting mouthfeel. Further analyses were carried out by continuous compression analysis using a creep meter, dynamic viscoelasticity measurement, and viscosity measurements with varied shear rate to compare the results of sensory tests (Table 2).

Continuous compression measurement using a creep meter indicated that pastry cream/custard using the modified starch P + E showed a continuous change in the parameter. Since the continuous compression measurement curve was comparable with that of wheat flour, whose melting mouthfeel was preferred, it was concluded that the compression analysis of pastry cream/custard reflected the melting mouthfeel.

Dynamic viscoelasticity parameters G' and G'' of pastry cream/custard made from wheat flour replaced by 10% w/w with Group P starches were closer to those of the products using wheat flour than the products replaced with Group AP starches. However, the difference in these parameters between P starch replaced product and AP starch replaced product was not observed, although the difference was observed by sensory evaluation [46]. Flow behaviors of pastry cream/custard were measured by using cone-plate viscometer, and the behaviors were expressed by thixotropic parameter and consistency index, which highly correlated with the sensory attributes such as smoothness, lightness, and melting mouthfeel [46]. Smaller values of thixotropic parameter and consistency index may represent smoother, lighter, and more melty feeling of pastry cream/custard. Pastry cream/custard product with P + E starch showed smaller thixotropic parameter and consistency index than that with P or AP + E starch. In addition, yield stress for the product with P + E starch was significantly higher than that with wheat flour. It was indicated that melting mouthfeel of pastry cream/custard could be evaluated by thixotropic parameter and consistency index in cone-plate viscosity measurement. It is necessary to accumulate data for further application of the method to evaluate melting mouthfeel of other foods.

5. Conclusions

Starch as a major constituent of starch gel dominates physical properties and applicability of the gel in food processing and cooking. *Warabi mochi* is often composed solely of water and starch with sugars added in some cases, and thus it reflects starch characteristics in its texture and accordingly its sensory quality. Therefore, the relatively dense food gel was adopted as a model system to reveal the effect of starch properties on the quality of starch gel foods. Among varieties of starches, sago starch was revealed to show high potentials such as high hardness, high cohesiveness, and low adhesiveness. Sago starch has not been utilized much in the food industry, and it has been difficult to obtain highly purified starch. However, high quality sago starch is now available due to recently extended plantation. Sago starch was applied to *warabi mochi* and *blancmange* in this paper, and it can be further applied to other starch gel foods such as *kudzukiri* (kudzu starch noodles) and *gomadofu* (sesame tofu, a tofu like kudzu starch gel with

Table 2 Correlation between sensory evaluation and mechanical parameters in dynamic viscoelasticity and flow behavior measurements

		Sensory Evaluation			
		smoothness	lightness	melting mouthfeel	overall evaluation
dynamic viscoelasticity	G'	0.012	0.028	−0.024	−0.087
	G''	−0.193	−0.196	−0.232	−0.301
flow behavior	thixotropic parameter	0.904*	0.950*	0.924*	0.844
	consistency index	0.839	0.817	0.823	0.934*

*Significantly correlated at $p < 0.05$

sesame paste) [41, 42]. Retrogradation of sago starch gel upon freezing and thawing was more efficiently suppressed than corn or potato starch gels when mixed with hydroxypropylated wheat starch. Further study will be required to reveal the effect of mixing modified and native starches on the application of the mixture to frozen starch gel foods.

Starch gel foods are often prepared by mixing water, starch, and sugars with other materials such as proteins, fats, and flavors. Scheffé's simplex lattice design method has often been applied to optimize the ratio of more than three food materials in cookery science. The method facilitates analyzing the effect of more than 2 food materials on food quality with minimum experimental trials. In its triangular lattice, an estimation curve corresponding to a specific physicochemical parameter enables to estimate optimal food compositions with the fixed parameter. In other words, based on the estimation curve, various compositions for one food with a specific physicochemical parameter can be suggested to respond to demands of patients and infants who may require for instance less fats or more proteins depending on their health conditions. Although it has not been very easy to depict the estimation curve, a method to facilitate the depiction was suggested [75]. It is expected to apply the method to various foods.

In the study on the effect of modified starches on the quality of pastry cream/custard, it was revealed that “melting mouthfeel” of the food was quite important as a sensory parameter. However, there was no established method to evaluate the parameter “melting mouthfeel”. This paper introduced possible parameters to evaluate the melty feelings: thixotropic parameter and consistency index by viscosity measurements with varied shear rates. The parameters are expected to be used in evaluating melt feel of other foods.

This paper reviewed applicability of sago starch and/or modified starch to starch gel foods, referring to the characteristics of Japanese traditional starches of warabi and kudzu. Starch gels can give foods specific textures which are not achieved by agar and gelatin gels. Desserts and confectionaries of starch gel including *warabi mochi*, *blanc-mange*, and *pastry cream/custard* play important roles in daily life as relaxation foods which may also contribute to joyful conversation over them. Research and development on starch gel foods from the viewpoint of cookery science

will be indispensable to make the foods further delicious giving nicer touch toward improved quality of life.

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