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# Comparison of physicochemical properties of jackfruit seed starch with potato and rice starches

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## ABSTRACT

The physicochemical properties of jackfruit seed starch (JSS) were investigated and compared with rice (RS) and potato (PS) starch. The amylose content of JSS (25%) was similar to PS (27%) but higher than RS (17%). The small granules of JSS (7.9  $\mu\text{m}$ ) was comparable to RS (9.7  $\mu\text{m}$ ), and both starches had A-type crystallinity. In contrast, PS had larger granules (43.4  $\mu\text{m}$ ) and displayed B-type crystallinity. The DSC results showed that peak gelatinization temperature of JSS (85.0°C) was significantly higher than RS (66.9°C) and PS (63.7°C), corresponding to higher pasting temperatures and lower swelling power at lower temperatures. There was no significant difference in stability between the starch gels after four freeze-thaw cycles. Formation of JSS gels with significantly higher hardness, chewiness and elastic modulus (G'), but lower fracturability demonstrated JSS ability to form strong gels. This would be beneficial for food applications requiring gelation with firm and elastic textural attributes.

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## KEYWORDS

Jackfruit seed; *Artocarpus heterophyllus*; starch; gel; rice; potato; gelatinization; retrogradation

## Introduction

The jackfruit (*Artocarpus heterophyllus*) is a highly seasonal fruit that is widely cultivated in tropical countries of the world due to its availability and low purchasing costs.<sup>[1]</sup> At present, India is the largest producer with a production of 1.4 million tons per annum.<sup>[2]</sup> Due to proximity, Singapore and other Southeast Asian countries import whole jackfruits mainly from Malaysia. The fruit can reach up to 36 kg in weight,<sup>[3]</sup> and it comprises of approximately 100 to 500 seeds which make up 8–15% of the whole fruit.<sup>[4,5]</sup> The seeds have been reported to be a good source of nutrients, containing approximately 14% protein and 80% carbohydrate.<sup>[6]</sup> The seeds also contain an abundance of starch, which makes up approximately 60–70% of its dry weight.<sup>[7]</sup> However, the seeds are often discarded as they are not usually consumed. In this study, we explore how the starch can potentially be further utilized by characterizing its properties and functionalities and comparing it to other commercially available starches. The findings would be of interest to small and medium enterprises (SMEs) in Singapore and other countries in the Southeast Asia region which may utilize jackfruit seed starch from jackfruit seed waste as a product ingredient.

The physicochemical properties of starch give rise to its unique functionality, whether in food applications such as its use as a thickener or gelling agent, as well as its nutritional properties which is of greater interest in recent years. Rice starch (RS) is widely used in Asia as an ingredient for foods

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such as rice noodles (vermicelli, *kuay teow*), while potato starch (PS) is commonly used as a thickener for gravies and sauces. Jackfruit seed starch (JSS) is therefore compared to both of these starches to better understand how its functionality may fit in existing applications of these starches. In Asia, many food products are pure starch gels such as starch noodles, steamed cakes, and desserts (*kueh*), and their physicochemical properties may have a direct influence on its metabolic impact, particularly on glycemic response. Furthermore, the physicochemical properties of the starch can have important control over the resulting sensory and textural properties, especially in products made of pure isolated starch.

Although various studies have reported the physicochemical properties of JSS of different botanical varieties, few have investigated the rheological and textural properties of the starch gels and/or compared to other commercially available starches.<sup>[7–9]</sup> Further, the jackfruit varieties in these studies were grown in China, which may not be reflective of the jackfruits grown in Malaysia which is then exported to Singapore and other Southeast Asian countries. Understanding these physical properties can provide a basis for determining the structure and texture of starch-based food products. The objectives of the present study were to isolate JSS from the Malaysian-grown jackfruit seeds and to determine the chemical composition, physicochemical properties, and functionalities of the starch, at the same time comparing it with rice and potato starches. The findings from this study could provide useful knowledge to product developers in the application of JSS in different food and non-food systems.

## Materials and methods

### Materials

Six jackfruits (*Artocarpus heterophyllus*) weighing an average of 20 to 25 kg each were imported from Muar, Johor, Malaysia (2.0631°N, 102.5849°E) via a local wholesale fruit seller in Singapore. The jackfruit seed cotyledons were extracted from jackfruits of ready-to-eat ripeness ( $14.1 \pm 1.4^\circ$  Brix). The white arils were physically removed from the cotyledons. The seeds with an intact brown spermoderm layer were coarsely ground (Retsch Grindomix GM 200; F-Kurt Retsch GmbH & Co. Haan, Germany), vacuum sealed and then stored at  $-20^\circ\text{C}$  until further starch extraction was carried out. Rice starch was purchased from Sigma-Aldrich, Singapore while potato starch (Windmill, Netherlands) was purchased from a local supermarket. All other chemicals used were of analytical reagent grade.

### Jackfruit seed starch extraction

Jackfruit seed starch was isolated from the coarsely ground jackfruit seeds using a modified method by Rengsutthi & Charoenrein.<sup>[9]</sup> The seeds were slurried in deionized water (1:2) using a magnetic stir plate and stirred continuously (500 rpm) for 3 h at room temperature. The slurry was passed through a sieve (75  $\mu\text{m}$ ) to remove the coarse fibers. The milky suspension obtained was then centrifuged at 8000 g (Rotina 380 R, Hettich, Germany) for 5 minutes, and the supernatant was decanted. The insoluble brown layer (likely to be protein) was scraped off and the starch pellet was transferred into a Duran bottle followed by the addition of 0.1 M sodium hydroxide to solubilize the remaining proteins. The suspension was kept at room temperature for 18 h with constant stirring. Subsequently, the suspension was centrifuged at 8000 g for 10 minutes ( $25^\circ\text{C}$ ) and rinsed with 0.1 M sodium hydroxide twice. The supernatant was decanted, and the remaining brown layer was also scraped off. The pellet was then rinsed with water and neutralized with 0.1 M hydrochloric acid until a pH of approximately 6.5 to 7.0 was achieved. The pellet was further rinsed with deionized water thrice to remove excess salt and centrifuged again at 8000 g for 10 minutes ( $25^\circ\text{C}$ ). The moisture content of the starch pellet suspension was adjusted to 70% before it was oven dried at  $40^\circ\text{C}$  for 18 h. The dried starch cake was milled with a blender (Tefal Blendforce BL307). The starch extraction yield from jackfruit

seeds based on the final mass of starch (dry basis) divided by the mass of jackfruit seed used in the extraction process (dry basis) was 24.5%.

### **Proximate analysis**

Starch samples were analyzed for moisture, protein, lipid and ash content. Nitrogen was determined using Kjeldahl block digestion unit and Vapodest distillation unit (Gerhardt Analytical Systems, Germany). The protein content was calculated from the nitrogen content ( $N \times 6.25$ ). The lipid content was determined based on Soxhlet extraction method using Soxtherm Rapid Extraction System (Gerhardt Analytical Systems, Germany). The ash content of samples was determined by drying the samples in a muffle furnace (Pyro MA 194, Milestone Scientific, Italy) at 525°C. Carbohydrate content was calculated by difference. All measurements were conducted in triplicates and averaged.

### **Total starch content**

Total starch content of the starches was determined using the Megazyme Total Starch Assay Kit (Megazyme, Bray, Ireland) based on the glucose oxidase peroxidase reaction. Briefly, 100 mg of sample was weighed into glass tubes and 0.2 mL of ethanol (80% v/v) and 2 mL of 1.7 M sodium hydroxide solution was mixed in to disperse the sample. The sample was stirred for 15 minutes to ensure no lumps were present. Next, 8 mL of sodium acetate buffer (600 mM, pH 3.8) containing 5 mM of calcium chloride was added into the tubes and vortexed. Then, 0.1 mL of thermostable  $\alpha$ -amylase and 0.1 mL of amyloglucosidase (3,300 U/mL) was dispensed into the tube. The sample was incubated at 50°C for 30 minutes and then cooled to room temperature. Then, 2.0 mL of aliquot was transferred into a microfuge tube and centrifuged (Centrifuge 5430 R, Eppendorf, Germany) at 13,000 rpm for 5 minutes. Aliquots of 1.0 mL was pipetted into tubes containing 4 mL of 100 mM sodium acetate buffer (pH 5.0). Subsequently, 0.1 mL of aliquot was transferred into each glass tube before adding 3.0 mL of glucose oxidase/peroxidase (GOPOD reagent). The tubes were incubated at 50°C for 20 minutes and the absorbance of the sample and standard (D-glucose) were measured at 510 nm in a UV-Vis spectrophotometer (Cary 60, Agilent, United States). A total of three replicates were analyzed.

### **Amylose content**

The amylose content of the starch samples was determined using the Megazyme amylose/amylopectin assay kit (Megazyme, Bray, Ireland). Briefly, starch was weighed and dispersed by heating in dimethyl sulfoxide. The starch lipids were removed by precipitating the starch in 95% v/v ethanol. The precipitated starch was recovered and dispersed in sodium acetate buffer. The amylose component was effectively separated from amylopectin based on the formation of a Concanavalin A lectin-amylopectin complex. The amylose which was present in the supernatant was enzymatically hydrolyzed to D-glucose and the absorbance was read at 510 nm in a UV-VIS spectrophotometer (Cary 60, Agilent, United States). The total starch, in a separate aliquot of sodium acetate buffer was also hydrolyzed to D-glucose and measured colorimetrically. A total of three replicates were analyzed.

### **Morphology and particle size distribution**

Starch suspensions (0.1% w/w, dry basis) were prepared and observed with a light microscope (Nikon Eclipse Ci, DS RI2, Japan) under polarized and normal light setting. Particle size distribution of the starches were analyzed by laser light diffraction using a Malvern Mastersizer 3000 (Malvern Instruments, Worcestershire, United Kingdom). A starch suspension of 5% w/w concentration was prepared for the analysis. Triplicate measurements were performed for each sample and the average volume-weighted mean diameter,  $D^{[3,4]}$  ( $\mu\text{m}$ ) measurements was reported.

### ***Starch polymorph (X-ray diffraction)***

The crystalline structure of the starches were obtained through X-Ray Diffraction (XRD) analysis using a Bruker D8 advance X-ray diffractometer, operated at 30 mA and 40kV, and using a Cu Ka source with a wavelength of 0.1541 nm. The scanning of diffraction angle (2Theta,  $2\theta$ ) was from 5° to 40° with a scanning speed of 10°/min and scanning step of 0.033°.

### ***Thermal properties (differential scanning calorimetry)***

The thermal properties of the starches were determined using a differential scanning calorimeter (DSC; DSC 214 Polyma, Netzsch, Selb, Germany). The starch suspension was adjusted to a moisture content of 70% w/w (dry basis). Approximately 10 mg of sample was weighed in an aluminum concavus pan and sealed with the lid inverted. A blank sample was used as a reference. The samples were scanned from 20°C to 120°C with a heating rate of 5°C/min. The onset temperature ( $T_o$ ), peak temperature ( $T_p$ ), conclusion temperature ( $T_c$ ) and enthalpy ( $\Delta H$ ) were obtained from the resulting thermogram. A total of three replicates were performed for the test.

### ***Swelling power***

Swelling power of starches were measured at 65°C, 75°C, 85°C, 90°C and 95°C. A 12 mL suspension (2% w/w, dry basis) was prepared in a 15 mL centrifuge tube. The tubes were immersed in a water bath at the respective temperature (65°C, 75°C, 85°C, 90°C and 95°C) for 30 minutes with continuous stirring. The tubes were then removed and cooled to room temperature before centrifuging at 6000 g for 10 minutes (Centrifuge 5430 R, Eppendorf, Germany). The supernatant was discarded, and wet sediment was weighed. The swelling power of starch was expressed as the ratio of wet weight sediment (g) to the initial dry sample weight (g).

### ***Freeze-thaw stability***

Starch suspensions (5% w/w, dry basis) were prepared and then heated in a 95°C water bath for 20 minutes with constant stirring. Next, 10 g of gel/paste was divided into 50 mL centrifuge tubes and stored at -20°C for 20 h followed by thawing at 30°C for 4 h in a water bath. A total of four freeze-thaw cycles were conducted. After each cycle, the tubes were centrifuged at 7000 g for 10 minutes (Centrifuge 5430 R, Eppendorf, Germany) and the amount of water expelled from the gel was measured. The cumulative values for expelled water were obtained after calculating each percentage of expelled water from the remaining gel. Syneresis was determined as the percentage of water expelled (g) to the initial gel weight (g).

### ***Pasting properties***

The pasting properties of starch samples were measured using a rheometer (MCR 102, Anton Paar, Graz, Austria) with a starch cell accessory. A starch suspension of 8% w/w concentration (dry basis) was prepared for the measurement. The samples were pre-sheared at 160 rpm for 5 minutes and then heated from 25°C to 50°C at a heating rate of 3°C/min, followed by 50°C to 95°C at 2°C/min. Then, the starch suspension was held at 95°C for 10 min and cooled to 50°C at a rate of 2°C/min. Lastly, it was maintained at 50°C for 10 minutes. The pasting temperature, peak viscosity, breakdown viscosity, final viscosity and setback viscosity were obtained from the pasting curve.

### Starch gel viscoelasticity

The rheological properties of the starch gels were studied using a rheometer equipped with a starch cell (MCR 102, Anton Paar, Graz, Austria). The starch suspension was prepared at 8% w/w concentration (dry basis) and pre-stirred at room temperature for 5 minutes (250 rpm) before transferring into the starch cell. The starch suspension was heated under constant rotational shearing at 160 rpm to a temperature close to its peak viscosity i.e. 85°C, 88°C, and 67°C for JSS, RS and PS, respectively. This ensures that the starch does not sediment during the oscillatory measurements. Then, the rotational mode was switched to oscillatory shear to evaluate the mechanical spectra. The samples continued to heat to 95°C under 0.1% strain and 1 Hz. Following this, samples were cooled from 95°C to 25°C at a cooling rate of 3°C per minute to monitor the gelation. The amplitude and frequency tests were carried out after the starch gels cooled from 95°C to 25°C. Amplitude sweep was performed at 25°C in the shear strain ( $\gamma$ ) range of 0.01 to 20% at a frequency of 1 Hz to determine the linear viscoelastic range. The frequency sweep of the gels were also conducted in the frequency range of 0.1 to 50 Hz under a shear strain of 0.1% in the linear viscoelastic region at 25°C. All rheological measurements were carried out in duplicates and parameters such as elastic modulus ( $G'$ ) and viscous modulus ( $G''$ ) were obtained.

### Starch gel texture

The textural properties of the starch gels were evaluated using a texture analyzer (TA.XT Plus, Stable Micro Systems, United Kingdom) with a flat cylindrical probe (P/75 mm). Starch gels were prepared at concentrations of 5%, 10%, and 15% w/w by heating to 95°C under continuous stirring for 20 min and cooled at 4°C for 24 h to allow gel maturation. Before the test, the gels were equilibrated at 25°C for 2 h, and the equipment was calibrated using a 5 kg load cell. A texture profile analysis (TPA) was performed at 25% strain to obtain gel parameters i.e. hardness, cohesiveness, springiness, and chewiness. A compression test at 70% strain was also performed to obtain fracturability of the gels. A total of five replicates were obtained for each gel concentration and strain.

### Statistical analysis

The statistical significant tests were performed using analysis of variance (ANOVA) at 95% confidence level. Significant differences among mean values were determined by Tukey's test.

## Results

### Proximate analysis and chemical composition

The proximate analysis and chemical composition of JSS, RS, and PS are as shown in Table 1. The yield of JSS was 24.5 g starch per 100 g dried seeds. The total starch content of JSS was 92.6%,

**Table 1.** Moisture, protein, lipid, ash, carbohydrate, total starch, and amylose content of jackfruit seed (JSS), rice (RS) and potato (PS) starches.

	Jackfruit Seed Starch (JSS)	Rice Starch (RS)	Potato Starch (PS)
Moisture	9.0 $\pm$ 0.0	11.02 $\pm$ 0.1	18.3 $\pm$ 0.0
*Protein	0.3 $\pm$ 0.0	0.5 $\pm$ 0.0	0.1 $\pm$ 0.0
*Lipid	0.4 $\pm$ 0.1	1.3 $\pm$ 0.2	1.4 $\pm$ 0.0
*Ash	0.3 $\pm$ 0.0	0.3 $\pm$ 0.1	1.2 $\pm$ 0.1
*Carbohydrates	99.0 $\pm$ 0.1	97.9 $\pm$ 0.2	97.3 $\pm$ 0.1
*Total starch	92.6 $\pm$ 1.6 <sup>a</sup>	91.4 $\pm$ 0.6 <sup>a</sup>	97.5 $\pm$ 1.1 <sup>a</sup>
Amylose (% w/w)	25.4 $\pm$ 0.4 <sup>a</sup>	17.3 $\pm$ 0.6 <sup>b</sup>	27.0 $\pm$ 1.3 <sup>a</sup>

\*Dry weight basis; <sup>†</sup>Amylose (%w/w) is based on % of starch; Different letters indicate a significant difference between starches.



indicating that the extraction method obtained a starch with purity comparable to the commercial RS and PS. As for the amylose content (% w/w), PS has the highest amylose, followed by JSS and RS. The three starches were classified under normal starches since the amylose content was between 15% and 35%.<sup>[10]</sup>

## Physicochemical properties

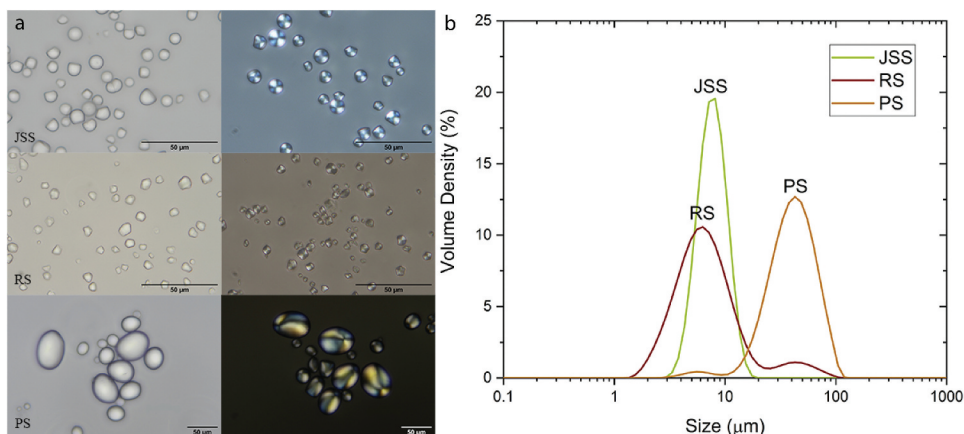
### Morphology

Starch morphology was visualized using a light microscope under normal and polarized settings, illustrating variations in granular size, birefringence, and shape (Figure 1a). The JSS granules were mainly spherical, while RS contained a mixture of polygonal and irregularly shaped granules. Potato starch granules were mostly large and oval. Under polarized light, all the starch granules exhibited birefringence with the 'Maltese cross'. The hilum of JSS was in the center of the Maltese cross whereas RS and PS both displayed an off-center hilum.

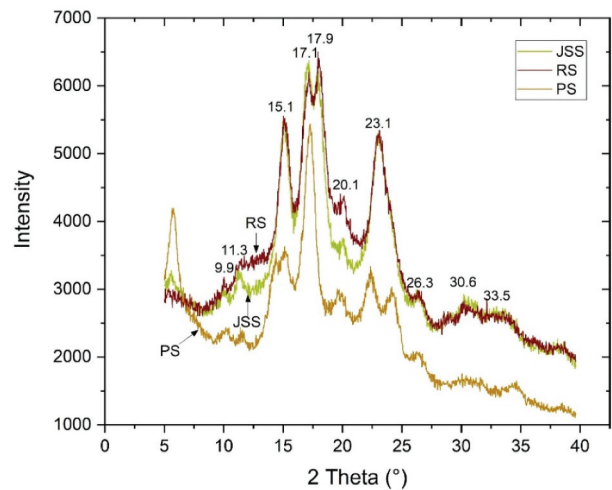
The particle size distribution curve of JSS, RS and PS are shown in Figure 1b. The average granule size based on D(4,3) was  $7.9 \pm 0.0$ ,  $9.7 \pm 0.5$  and  $43.4 \pm 0.2$   $\mu\text{m}$  for JSS, RS and PS respectively, which were in agreement with that observed under light microscopy (Figure 1a). The JSS granules were significantly smaller compared to RS and PS. In terms of particle size distribution, JSS had a narrower size distribution compared to the other starches. These values were within the granule size range of 7–11  $\mu\text{m}$  reported by Rengsutthi & Charoenrein.<sup>[9]</sup> The small granule size of JSS was also found to be comparable to RS, which is the smallest known granule amongst cereal grains.

### Crystalline structure

The X-ray diffraction pattern indicates the presence of the ordered phase, mainly determined by the alignment of the linear amylose. The amylose chains behave like crystalline planes of solid crystal when investigated by X-rays.<sup>[11]</sup> The angles in which peaks are observed are due to diffractions of the lattice organized in a random orientation. The XRD of the three starches (JSS, RS, and PS) are as shown in Figure 2. The JSS and RS showed strong diffraction peaks at  $2\theta$  of  $11^\circ$ ,  $15^\circ$ ,  $17.1^\circ$ ,  $17.9^\circ$  and  $23.1^\circ$  suggesting A-type crystallinity.<sup>[12]</sup> Potato starch displayed peaks at approximately  $15.2^\circ$ ,  $17.2^\circ$ ,  $22^\circ$  and



**Figure 1.** (a) Light micrographs of jackfruit seed starch (top; JSS), rice starch (middle; RS) and potato starch (bottom; PS) viewed under normal light (left) and polarized light (right); scale bar represents 50  $\mu\text{m}$ ; (b) particle size distribution of JSS, RS and PS.



**Figure 2.** X-ray diffraction patterns of jackfruit seed starch (JSS), rice starch (RS) and potato starch (PS).

24° of 2θ which indicates B-type crystallinity.<sup>[1213]</sup> The type of crystallinity observed for JSS and RS agrees with those reported by Chen et al.<sup>[5]</sup> and Mohan et al.<sup>[6]</sup> respectively.

### Thermal properties

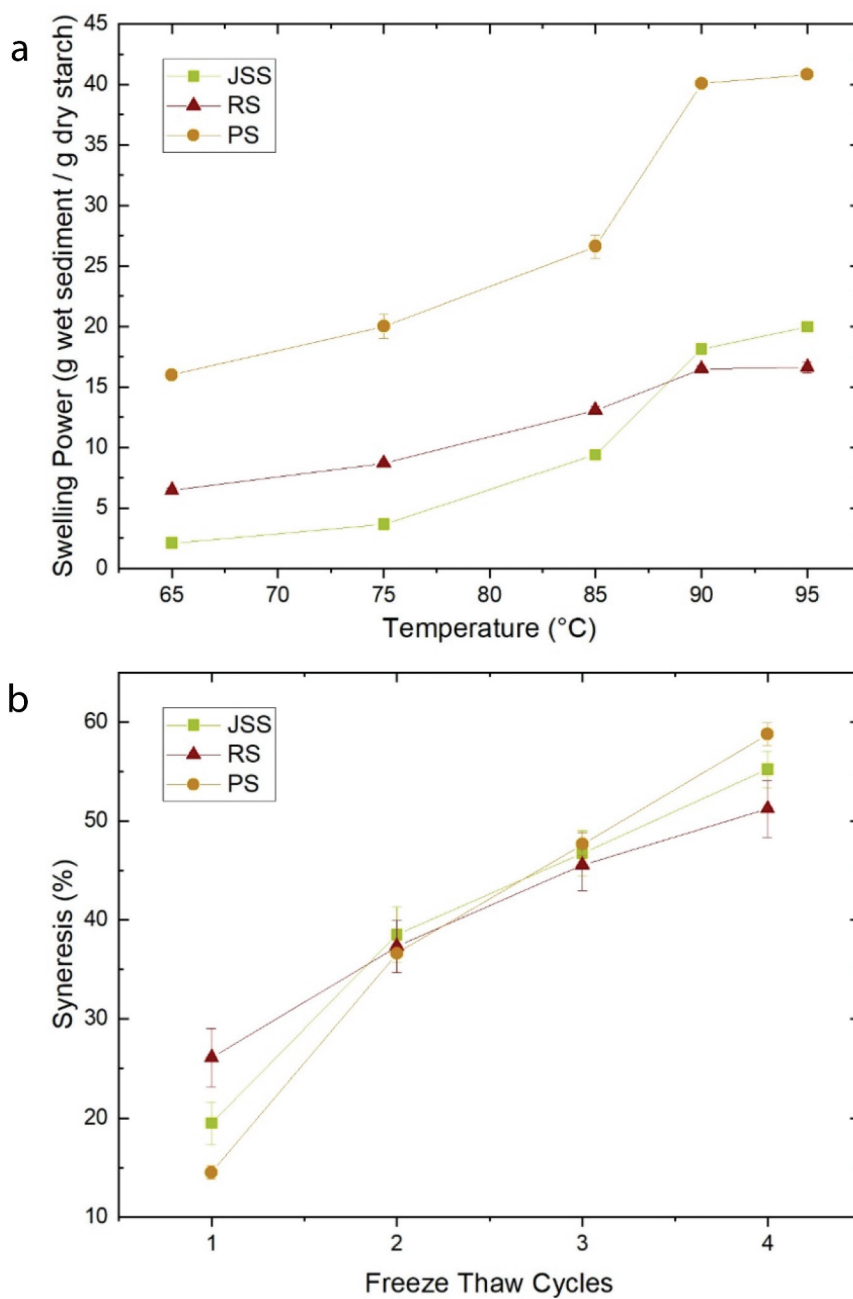
The gelatinization transition temperatures i.e. onset temperature ( $T_o$ ), peak temperature ( $T_p$ ) and conclusion temperature ( $T_c$ ) of JSS, RS and PS were measured using differential scanning calorimetry (DSC) (Table 2). The onset temperature represents the start of gelatinization with the melting of the weakest crystallites and the peak temperature indicates complete loss of birefringence during gelatinization.<sup>[14,15]</sup> The conclusion temperature is the temperature at which amylopectin double helices dissociates marking the completion of gelatinization. From the thermograms, JSS exhibited two endothermic peaks, the first and second peak had an onset temperature of 70.0°C and 81.7°C respectively. The latter was recorded as the gelatinization onset temperature. The presence of two peaks has also been observed by Tran et al.<sup>[4]</sup> and was attributed to two different groups of crystalline structure located in different starch granules or different cavities within the same granule. The values obtained in this study were also in good agreement with their results.<sup>[4]</sup> Comparing the three starches, the onset of gelatinization for JSS occurred at a significantly higher temperature ( $81.7 \pm 0.5^\circ\text{C}$ ) than RS and PS. Additionally, the peak and conclusion temperatures recorded were also significantly higher for JSS. Gelatinization occurred at similar temperatures for RS ( $61.7 \pm 1.1^\circ\text{C}$ ) and PS ( $59.8 \pm 0.2^\circ\text{C}$ ), although RS had a significantly higher peak temperature. The gelatinization enthalpy ( $\Delta H$ ) was also derived, which represents the energy required to break intermolecular bonds during gelatinization. The  $\Delta H$  of JSS ( $5.4 \pm 1.2 \text{ J/g}$ ) and PS ( $5.7 \pm 0.8 \text{ J/g}$ ) were significantly higher than RS

**Table 2.** Thermal properties i.e. onset ( $T_o$ ), peak ( $T_p$ ) and conclusion ( $T_c$ ) temperature and gelatinization enthalpy ( $\Delta H$ ) of jackfruit seed starch (JSS), rice starch (RS) and potato starch (PS).

	Jackfruit Seed Starch (JSS)	Rice Starch (RS)	Potato Starch (PS)
$T_o$ (°C)	$81.7 \pm 0.5^a$	$61.7 \pm 1.1^b$	$59.8 \pm 0.2^b$
$T_p$ (°C)	$85.0 \pm 0.8^a$	$66.9 \pm 0.1^b$	$63.7 \pm 0.2^c$
$T_c$ (°C)	$91.1 \pm 1.2^a$	$74.7 \pm 1.2^b$	$72.3 \pm 1.0^b$
$\Delta H$ (J/g)	$5.4 \pm 1.2^a$	$3.1 \pm 0.7^b$	$5.7 \pm 0.8^a$

\*Different letters indicate a significant difference between starches.





**Figure 3.** (a) Swelling power and (b) freeze-thaw stability of jackfruit seed starch (JSS), rice starch (RS) and potato starch (PS).

( $3.1 \pm 0.7$  J/g), although there were no required significant differences between JSS and PS. A higher  $\Delta H$  is often associated with increased energy required to induce gelatinization which reflects the granules highly ordered crystallinity and heat-resistant properties.

## Functional properties

### Swelling power

All three starches increased in swelling power with increasing temperature (Figure 3a). Potato starch had the greatest swelling power at all temperatures. At temperatures 65°C, 75°C and 85°C, JSS had a lower swelling power than RS and PS. As swelling is temperature dependent, a higher swelling power could be expected when starch is heated above the gelatinization temperature. From 85°C to 90°C, a huge increment in swelling power of JSS was observed due to heating above the peak gelatinization temperature ( $T_p = 85.0^\circ\text{C}$ ), leading to the disruption of hydroxyl groups. Consequently, more water molecules could associate with the exposed hydroxyl groups via hydrogen bonding, resulting in more swelling.<sup>[16]</sup> The swelling power of JSS at 1% w/w has also been evaluated by Dutta et al.<sup>[8]</sup> They reported a swelling power of approximately 2 g/g, 3 g/g, 13 g/g and 17 g/g at temperatures 65°C, 75°C, 85°C, and 95°C respectively.<sup>[8]</sup> These values were fairly similar to the present study with the exception of swelling power at 85°C. The slight variations could be attributed to the different jackfruit varieties, geographic origin, and seasonal variations.

### Freeze-thaw stability

During the freezing process, ice crystals form within the starch gels and phase separation occurs. When the gel is thawed, the gel is composed of a starch-rich and starch-deficient phase.<sup>[17]</sup> The repeated freezing and thawing process exacerbates the phase separation and ice growth. Generally, the freeze-thaw stability of the starch system is considered inferior when more water gets expelled.<sup>[18]</sup> A total of four freeze-thaw cycles (FTC) were performed to measure the % syneresis of starch at 5% w/w concentration (dry basis) (Figure 3b). Syneresis of the three starches increased progressively with the number of freeze-thaw cycles. Comparing the three starches, PS had the highest % syneresis ( $58.8 \pm 1.2\%$ ) at the end of four FTC, followed by JSS ( $55.2 \pm 1.8\%$ ) and RS ( $51.2 \pm 2.9\%$ ). However, these differences in % syneresis were not statistically significant.

### Pasting properties

The pasting properties of the starches were determined using a rheometer, and the pasting curve is as shown in Figure 4. The parameters that were measured include pasting temperature, peak viscosity, breakdown viscosity, final viscosity, and setback viscosity. The pasting temperature of JSS ( $83.9 \pm 0.2^\circ\text{C}$ ) was significantly higher than that of RS ( $69.1 \pm 0.5^\circ\text{C}$ ) and PS ( $64.0 \pm 0.2^\circ\text{C}$ ).

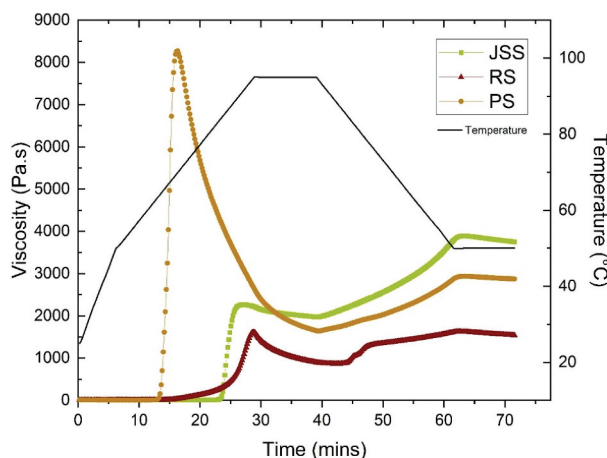


Figure 4. Pasting curves of jackfruit seed starch (JSS), rice starch (RS) and potato starch (PS).

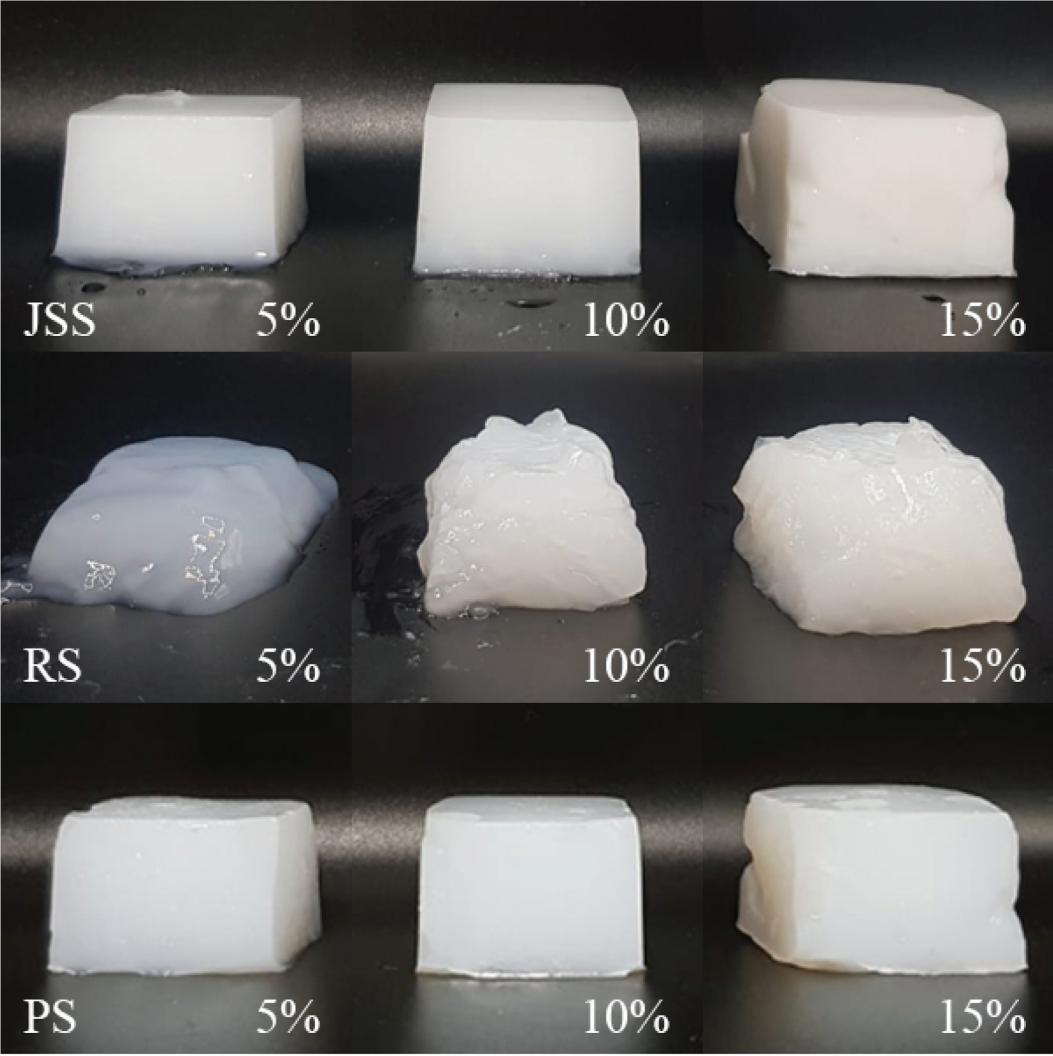
These temperatures obtained from the pasting curve corresponded well to the values obtained from the DSC (Table 2). The peak viscosity is an important parameter that represents the swelling extent and water holding capacity in starches. Potato starch obtained the highest peak viscosity ( $8271 \pm 82$  mPa.s), followed by JSS ( $2262 \pm 22$  mPa.s) and RS ( $1620 \pm 42$  mPa.s). This corresponded well with the trends in swelling power ( $PS > JSS > RS$  at  $95^\circ\text{C}$ ). From the pasting curve, the breakdown viscosity which is the difference between the peak and trough viscosity was also derived. A lower breakdown signifies the starch resistance to mechanical shear during the holding periods and constant shearing. Amongst the three starches, JSS had the lowest breakdown ( $286 \pm 8$  mPa.s), followed by RS ( $755 \pm 0$  mPa.s) and PS ( $6628 \pm 54$  mPa.s). The setback viscosity which is calculated based on the difference between the final and peak viscosity indicates the re-association of starch molecules after breakdown. Interestingly, JSS exhibited a positive setback ( $1489 \pm 20$  mPa.s) unlike PS ( $-5398 \pm 48$  mPa.s) and RS ( $-72 \pm 1$  mPa.s) which obtained a negative setback. The positive setback viscosity also indicates the inclination of starch molecules to reassociate i.e. retrograde for gel formation. Generally, a higher setback would benefit applications such as Asian noodles, where a stronger starch gel would impart sensory characteristics like cohesiveness.<sup>[19]</sup> The other parameter that correlates to the quality of the starch sample is the final viscosity. The highest final viscosity was seen in JSS ( $3751 \pm 24$  mPa.s) followed by PS ( $2873 \pm 35$  mPa.s) and RS ( $1548 \pm 28$  mPa.s). Aside from the sensory properties, stronger gels are preferred for noodles because they are more stable to boiling and will maintain its structure.<sup>[20]</sup> It has also been suggested that the starch used for preparing noodles should restrict swelling and maintain or increase its viscosity during continued heating and shearing.<sup>[21]</sup>

## Gelation

Starch gels were prepared from JSS, RS and PS at different concentrations (5% w/w, 10% w/w and 15% w/w) by heating to  $95^\circ\text{C}$  and cooling at  $4^\circ\text{C}$  for 24 h (Figure 5). Texture Profile Analysis (TPA) and fracturability of JSS and PS gels at different concentrations were evaluated using 25% and 70% strain, respectively. The textural parameters, i.e. hardness, springiness, cohesiveness, and chewiness obtained from the TPA are shown in Table 3. The textural properties of RS gels were not measured as the gels were not self-supporting and did not have a consistent and flat surface area for contact with the compression probe. At 15% w/w, the RS gel collapsed when left to equilibrate at room temperature.

The hardness was defined as the maximum peak force and the springiness parameter refers to the elasticity, and it is an indication of how well the gel springs back after the first compression.<sup>[22]</sup> The other parameter which is cohesiveness refers to how well the starch gel maintains its structure after the first compression. Lastly, the chewiness is the measure of the energy required to masticate the gel.<sup>[23,24]</sup> At highest strains, fracturability measured refers to the maximum force at the rupture point of the gel. From the TPA results, JSS gels at all three concentrations (5%, 10%, and 15%) were significantly harder than PS gels. In terms of fracturability, JSS gels had significantly lower fracturability compared to PS gels at 5% concentration. However, fracturability of JSS gels were significantly higher than PS gels at 10% and 15%. There was also no significant difference for springiness and cohesiveness between JSS and PS gels. The chewiness of JSS gels at the three concentrations were also significantly higher than PS gels.

The rheological properties of the starch gels were characterized via temperature sweep and frequency sweep test. When a starch is heated in excess water and cooled, it forms a gel or paste. Retrogradation of the leached components and interaction between molecules inside the starch granule strengthens the gel structure, resulting in increased  $G'$  and  $G''$ .<sup>[25]</sup> In this study, the gelation process of the starch gels (8% w/w) was monitored from  $95^\circ\text{C}$  to  $25^\circ\text{C}$  (Figure 6a). It can be concluded that all three starches formed a gel as  $G'$  was higher than  $G''$ . The JSS gel was shown to have a slightly lower  $G'$  than PS gel during the initial cooling phase. At the end of the cooling cycle ( $25^\circ\text{C}$ ), the highest  $G'$  was observed in JSS (379 Pa) gels, followed by PS (304 Pa) and RS (202 Pa) gels (Figure 6a). The

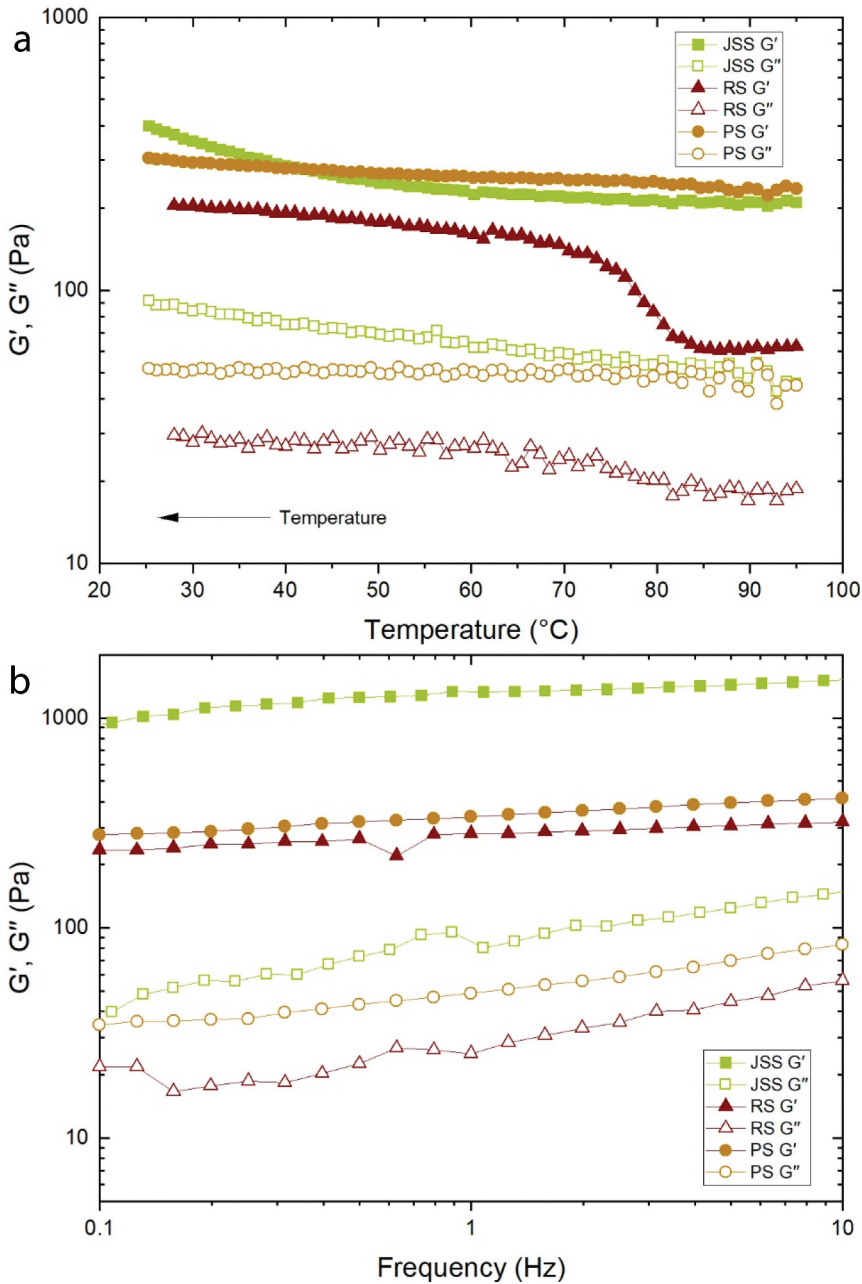


**Figure 5.** Visual appearance of jackfruit seed starch (JSS), rice starch (RS) and potato starch (PS) at 5, 10 and 15% w/w.

**Table 3.** Texture profile analysis (TPA) and fracturability of jackfruit seed starch (JSS) and potato starch (PS).

Concentration (% w/w dry basis)		Parameter				
		Hardness (g)	Springiness	Cohesiveness	Chewiness (g)	Fracturability (g)
5	JSS	60.5 ± 1.0 <sup>a</sup>	1.00 ± 0.00 <sup>a</sup>	1.00 ± 0.00 <sup>a</sup>	60.4 ± 1.0 <sup>a</sup>	105.9 ± 19.5 <sup>a</sup>
	PS	27.5 ± 3.2 <sup>b</sup>	1.00 ± 0.00 <sup>a</sup>	0.99 ± 0.03 <sup>a</sup>	27.1 ± 3.8 <sup>b</sup>	198.6 ± 6.8 <sup>b</sup>
10	JSS	372.7 ± 20.5 <sup>a</sup>	0.99 ± 0.01 <sup>a</sup>	0.96 ± 0.01 <sup>a</sup>	352.7 ± 20.8 <sup>a</sup>	853.0 ± 117.8 <sup>a</sup>
	PS	182.8 ± 34.1 <sup>b</sup>	0.98 ± 0.02 <sup>a</sup>	0.95 ± 0.01 <sup>a</sup>	168.6 ± 31.6 <sup>b</sup>	638.5 ± 85.3 <sup>b</sup>
15	JSS	1096.2 ± 77.9 <sup>a</sup>	0.98 ± 0.02 <sup>a</sup>	0.95 ± 0.02 <sup>a</sup>	1018.1 ± 90.8 <sup>a</sup>	2056.5 ± 108.7 <sup>a</sup>
	PS	719.5 ± 156.9 <sup>b</sup>	0.98 ± 0.06 <sup>a</sup>	0.91 ± 0.02 <sup>a</sup>	637.7 ± 108.6 <sup>b</sup>	1223.0 ± 185.9 <sup>b</sup>

<sup>a,b</sup>Different letters indicate a significant difference between starches for a particular parameter at the same gel concentration.



**Figure 6.** (a) Temperature sweep of JSS, RS and PS (8% w/w) conducted from 95°C to 25°C at 0.1% strain and 1 Hz; (b) Frequency sweep of JSS, RS and PS (8% w/w).

changes in  $G'$  and  $G''$  of PS were not as apparent because the gel structure was already developed during the heating stage.<sup>[26,27]</sup> As for RS, a sharp increase in  $G'$  was observed from 80°C to 70°C. From the frequency sweep, the highest  $G'$  was observed in JSS throughout the frequency range. At a frequency of 1 Hz,  $G'$  was recorded to be 1332 Pa, 346 Pa and 286 Pa for JSS, PS and RS gels, respectively (Figure 6b). The drastic increase in the  $G'$  of JSS after cooling corresponds with the positive setback that was observed in the pasting curve.

## Discussion

The application of starches in different food systems is dependent on their physicochemical properties. The characterization techniques employed in this study presented a clear comparison of the physical properties of JSS, RS and PS tested under the same conditions. From the results, three key useful characteristics were identified for JSS. These useful characteristics include the relatively small and monodispersed granule size, the ability to withstand relatively high processing temperature before undergoing gelatinization, and its ability to form firm starch gels with unique textural attributes. In Asia, rice starch remains one of the most important carbohydrate sources in the manufacture of a variety of snacks (*kuehs*), desserts and puddings. Jackfruit seed starch which has until now been an under-exploited starch may provide new opportunities in the development of a variety of foods. A characteristic feature of Asian snacks is their unique mouthfeel, texture and organoleptic properties.

Small starch granules can possibly play an important role as fat mimetics as their small granule size with controlled swelling during heating may impart the sensation of creaminess.<sup>[28]</sup> Soft solids micron-size particles of <50 µm can generally influence oral somato sensation and potentially act as fat mimetics in low fat dressings, sauces and frozen desserts.<sup>[29,30]</sup> Additionally, starch is often used as a filler in comminuted meat protein gels, the particle size range has been suggested as one of the factors influencing the stability of these protein gels, where a narrow size distribution of 1–20 µm is preferred.<sup>[31]</sup> Beyond this range, the ability of particles to support the capillary network throughout the protein gel is reduced.<sup>[31]</sup> Therefore, the small JSS granules could prove beneficial as a texture improver for tumbled meat products where the granules can possibly penetrate crevices and pores of meat structures.<sup>[31]</sup> Moreover, the freeze-thaw stability results showed that JSS gels performed better than RS for the first freeze-thaw cycle, although subsequent freeze-thaw cycles saw similar extents of syneresis and freeze-thaw stability to RS and PS. A study on starches of different botanical origins has demonstrated that amylose content and syneresis retrogradation were positively correlated.<sup>[32]</sup> In the present findings, a significant difference in % syneresis was observed between PS and RS. However, no significant difference in syneresis was observed between JSS and RS despite the difference in amylose. Therefore, syneresis has been proposed to be influenced not only by amylose to amylopectin ratio but also the molar mass amylose and amylopectin as well as the degree of branching of amylopectin.<sup>[33]</sup> Taken together, these results support applications of JSS in frozen meat products to potentially prevent drying, shrinkage and also maintaining a moist texture.

The ability to withstand harsh processing conditions is another important factor in the manufacture of starch-based products. Amongst the three starches, JSS had the highest gelatinization transition temperatures and pasting temperature. The JSS having the highest gelatinization temperature reflects that the crystallites within the lattice were more 'perfect' and had a higher degree of order. The higher  $T_c$  exhibited by JSS also suggests a more rigid granule structure compared to RS and PS.<sup>[15]</sup> Starches with A-type crystallinity has been found to gelatinize at higher temperatures compared to B-type starches. This is because the glucose helices in B-type starches are less packed, leaving room for water molecules between branches.<sup>[10,34]</sup> Despite both JSS and RS having A-type crystallinity and small starch granule size, the gelatinization transition temperatures of JSS was significantly higher than RS.

The heat stability of JSS was further illustrated in the pasting curve whereby JSS had significantly higher pasting temperature than RS and PS. According to Falade and Okafor,<sup>[35]</sup> pasting temperature is influenced by particle size in which bigger granules would be less resistant to heating and rupture. However, this observation is not always consistent across starches of different botanical origins.<sup>[36]</sup> Other factors such as the degree of amylose and amylopectin packing within the starch granules could also contribute to starch gelatinization. The heat and shear-resistant characteristic of JSS was also demonstrated by its low breakdown viscosity, which suggested strong cohesive forces within the starch granules.<sup>[37]</sup> Moreover, the final viscosity of JSS was the highest among the three starches, indicating its ability to form a strong self-supporting gel. These unique properties imply that JSS has the ability to retain the viscosity of starch-based sauces and gravies of retorted products.



The gel forming ability of JSS was comparable to PS as both starch gels have good shape retention compared to RS at 5% w/w and above (Figure 5). The TPA measurements at 5% showed that JSS had significantly higher hardness and chewiness, but also lower fracturability ( $p < .05$ ) as compared to PS. However, fracturability of JSS gels were significantly higher than PS gels at 10% and 15% concentration. The viscoelasticity of the JSS gels determined through rheological measurements were consistent with the TPA and pasting results as the hardness values and positive setback viscosity agreed well with the higher  $G'$  obtained. From the higher  $G'$  values across all frequencies, it also points that JSS gels had a stronger structure than PS and RS. Typically, a higher  $G'$  is evident of higher elasticity and rigid structure due to high degree of chain associations by both amylose and amylopectin during retrogradation. According to Patindol et al.<sup>[38]</sup> the association involves amylose and long amylopectin chains, and a higher amylose content is ascribed to higher setback. Nonetheless, setback viscosity significantly differed for JSS and PS with similar amylose content, suggesting amylose content only partially contributed to gel structural strength. The unique combination of textural attributes suggest that JSS can potentially be applied in many starch-based foods to provide unique sensorial experience such as the springy-chewy attribute. The chewiness attribute is an important textural attribute in Asian starch-based foods such as *chwee kueh* (water rice cake) or rice noodles. In addition, JSS could potentially aid in maintaining the 'just about right' firmness (Al Dente) textural attribute in pasta products.<sup>[39,40]</sup> The gelling ability also supports the suitability of JSS in jellies, confectionary fillings, or restructured foods.

Further studies could include the determination of the JSS molecular parameters such as the molar mass of amylopectin and amylose, as well as their structural conformation to elucidate the mechanism behind high gelatinization temperatures and gel strengths. Further work may also include the application of JSS in selected food systems to determine consumer acceptance and how JSS could influence digestibility and glycemic response in the gastrointestinal track. The knowledge will uncover useful functional applications of JSS which would otherwise be discarded as waste during jackfruit processing. Differences in jackfruit varieties may lead to differences in starch structure and functionality, and therefore the findings in this study may be limited to jackfruits cultivated in Muar, Malaysia, and exported to Singapore.

## Conclusion

The physicochemical properties i.e. composition, amylose content, morphology, particle size, crystalline structure, thermal properties, pasting properties, swelling power, freeze-thaw stability, and gelation of JSS were evaluated and compared to RS and PS in this study. Three key characteristics were identified for JSS in contrast to RS and PS, which include the heat stability, ability to form strong starch gels and small monodispersed starch granules. This study has shown that JSS could potentially be used as an alternative starch in a wide range of food products. The results obtained from this work also facilitates further research which will widen the applications of JSS to confer beneficial physical functional properties, sensory and nutritional properties in food products. This opens up the possibility of using JSS as a novel source of starch to develop new and unique foods for the Asian and global markets.

## Disclosure statement

The authors declare no conflict of interest.

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