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Research Article

Comparison of structural and physicochemical properties of starches from five coarse grains

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ABSTRACT

Starch, one of the most important components of coarse grains, has received widespread attention because of its prominent potential health benefits. In the present study, we isolated starches from the grains of sorghum, tartary buckwheat, common buckwheat, mungbean, and pea and studied their structural and physicochemical properties. These five starches all showed the distinctive "Maltese cross" effect (birefringence) but significantly differed in morphology, size, and complexity of granules. Sorghum starch exhibited the lowest amylose content and highest weight-average molar mass. Mungbean contained more short amylopectin [degree of polymerization (DP) 6–12 = 23.4%]. Pea starch exhibited the highest amylose content, highest amylopectin average chain length, and lowest weight-average molar mass. The starches of sorghum, tartary buckwheat, and common buckwheat showed A-type crystallinity, whereas those of mungbean and pea showed C-type crystallinity. Our results provide useful information for the application of coarse grain starches in diverse industries.

1. Introduction

Coarse grains, including sorghum, foxtail millet, proso millet, buckwheat, barley, oat, and beans, have received widespread attention because of their prominent potential health benefits. Sorghum (Sorghum bicolor L.), a traditional food, is considered to play a role in the prevention of some diseases such as diabetes, cancer, cardiovascular disease, and dyslipidemia (Cardoso, Pinheiro, Martino, & Pinheiro-Sant'Ana, 2017). Tartary buckwheat (*Fagopyrum tataricum* (L.) Gaertn.) and common buckwheat (*Fagopyrum esculentum* Moench.) are rich in flavonoids and are typically used as functional foods. Mungbean (*Vigna radiata* L.) and pea (*Pisum sativum* L.) are important legumes, the total protein content of which ranges from 20% to 30%. The enzymatic hydrolysates of their two proteins demonstrate health benefits, and their protein and fiber are often used as food or industrial additives.

Starch is one of the most important components in crop kernels. Interest in finding new starch sources with novel and unique properties is increasing in different industries (Guo, Lin, Fan, Zhang, & Wei, 2018), because starches from different plants have different applications. Coarse grain starches are gradually being studied because of their special properties. However, most studies have focused on the functional components of the five coarse grains mentioned in the present study. During the processing of coarse grain products, a high proportion of starch remains following the extraction of functional ingredients. Therefore, research on the starches of these grains is important to promote the consumption and potential use of coarse grains.

Currently, some coarse grain starches are being exploited and utilized in the food industry and favored by consumers. Sorghum starch is a raw material for porridge, ethanol, couscous, and mayonnaise (Ali, Waqar, Ali, Mehboob, & Hasnain, 2015; Zhu, 2014), and vermicelli is often produced from mungbean and pea starches (Li, Xing, Sun, Chu, & Xiong, 2015; Yan, Liu, Li, & Shen, 2010). However, compared with starches from staple crops, such as wheat (Huang & Lai, 2010), corn, and rice (Onyango, Mutungi, Unbehend, & Lindhauer, 2011), coarse grain starches, particularly buckwheat starches are not widely used in the food industry, which is attributed to the insufficient research on their structural and physicochemical properties. Properties of coarse grain starches, including morphology, amylose, crystalline structure, starch paste properties, pasting properties, and hydrolysis and digestion properties, have been reported by certain groups (Cruz, Silva, Santos, Zavareze Eda, & Elias, 2015; Gao et al., 2016; Kim, Woo, & Chung, 2018; Wang, Sharp, & Copeland, 2011). However, reports describing

Abbreviations: APTS, 1-aminopyrene-3,6,8-trisulfonic acid; BD, breakdown viscosity; FSC, forward-scattered light; FV, final viscosity; *Mw*, weight-average molar mass; PT, peak time; PTM, Pasting temperature; PV, peak viscosity; *Rz*, average radius of gyration; SB, setback viscosity; SSC, side-scattered light; Tc, conclusion temperature; To, onset temperature; Tp, peak temperature; TV, trough viscosity; ρ, molecular density; Δ*H*, gelatinization enthalpy

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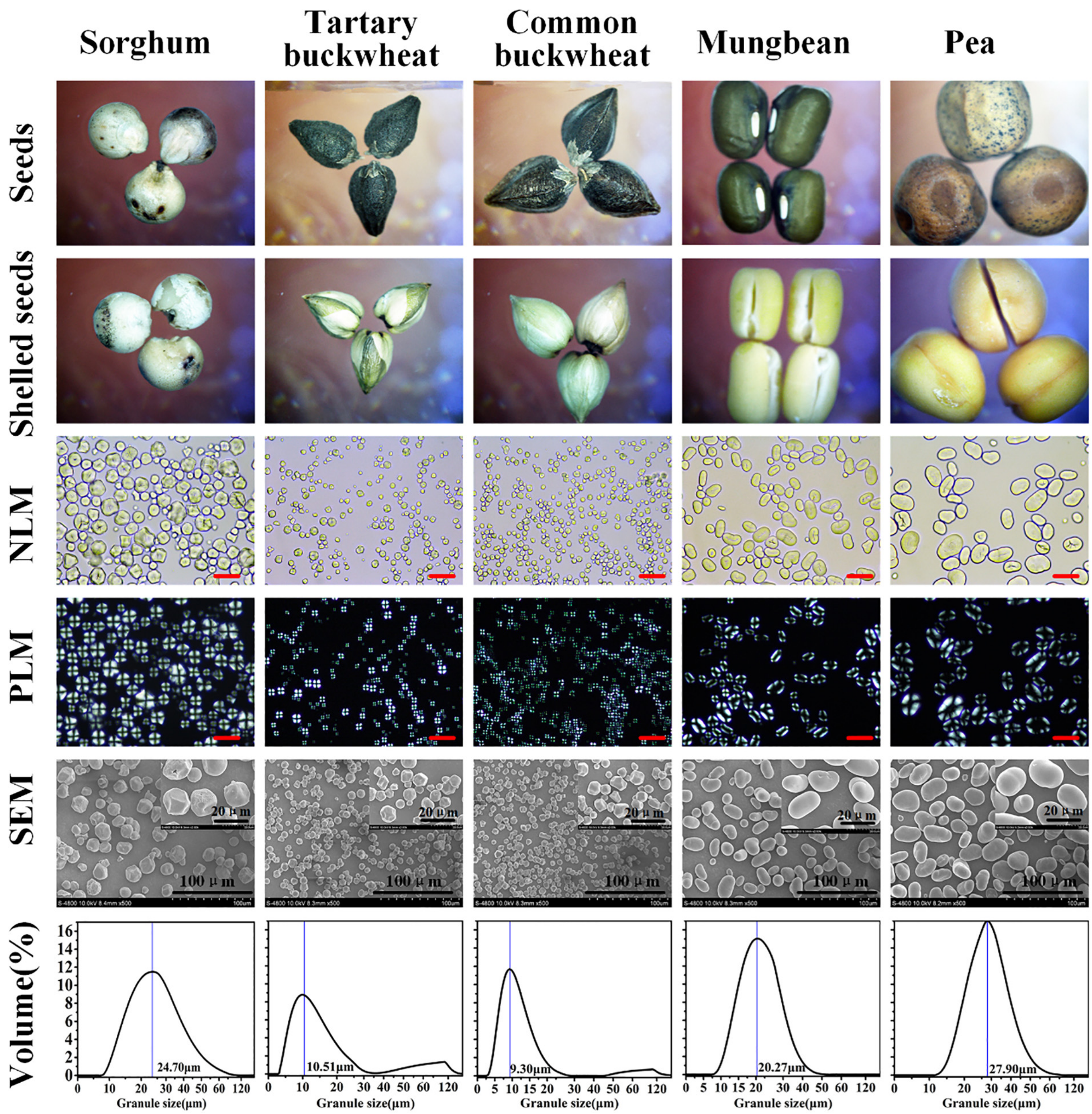

Fig. 1. Photographs of seeds and shelled seeds; morphologies of starch granules under normal light microscope (NLM), polarized light microscope (PLM), and scanning electron microscope (SEM); and granule size distribution of starches. Red scale bar = 50 μm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

average molecular weights, chain length distribution of amylopectin, or flow cytometry in starches of coarse grains are scarce. In the present study, we isolated starches from the grains of sorghum, tartary buckwheat, common buckwheat, mungbean and pea and investigated their structural and physicochemical properties. Our results will provide a deeper understanding and useful information for the application of coarse grain starches in food and nonfood industries.

2. Materials and methods

2.1. Materials

The seeds of sorghum, tartary buckwheat, common buckwheat, mungbean, and pea crops were studied (Fig. 1). Sorghum (Liaonian 3) was obtained from Liaoning Academy of Agricultural Sciences. Tartary buckwheat (Xinong 9940), common buckwheat (Xinong 9978), mungbean (Xilv 1), and pea (Xiwan 1) were provided by Northwest A&F University.

2.2. Starch isolation

Starches were isolated following the methods of Zhang, Feng et al. (2018) and Gao et al. (2016) with some modifications. The seeds (200 g) were rinsed, shelled, and then pulverized into flour (FW–100D, XinBoDe LTD, Tianjin, China), of which 100 g was suspended in 0.2% (w/v) H_2SO_4 and left overnight at room temperature. The suspension was filtered with 80 and 100-mesh sieves, and centrifuged at 2000*g* for 10 min; then the supernatant removed. The sediment was dissolved in 0.2% NaOH and centrifuged (2000*g*, 10 min) again to remove impurities. Subsequently, the deposit was washed with distilled water and centrifuged at 2000*g* for 10 min. The above steps were repeated until the color of the supernatant was clear. The remaining deposit was then mixed with acetone (40 mL) and centrifuged at 2000*g* for 10 min. The final starch pellets were dried in a fume hood and an 80-mesh sieve was used to eliminate lumps.

2.3. Chemical composition of flour and starch

The fat, protein, and total starch contents were obtained by Soxhlet extraction, Kjeldahl method, and anthrone spectrophotometric method, respectively (Yang et al., 2018). The amylose content was measured following the method described by Yang et al. (2018).

2.4. Morphology of starch by microscopy

A 10% (w/v) starch suspension in 50% glycerol was observed by using an Olympus BX53 polarized light microscope (Olympus, Tokyo, Japan) under normal and polarized light. In order to observe surface structures, the samples were sputtered with gold/palladium at a ratio of 60:40 and observed using a scanning electron microscope (S4800, Hitachi, Tokyo, Japan).

2.5. Size analysis of starch granules

Granule size analysis was carried out using Mastersizer 2000 (Malvern, England) (Cai et al., 2014). Starch staining, sample preparation, and flow cytometry analysis followed the method of Zhang, Feng et al. (2018), with some modifications, including the use of distilled, deionized H_2O as the starch suspension reagent and unstained starch granules as the negative control.

2.6. Molecular weight distribution of starch

Weight-average molar mass (*Mw*) was analyzed by using an Agilent PL-GPC 220 high temperature chromatograph (Agilent Technologies Inc., Santa Clara, CA, USA) and multiangle laser light scattering (Zeng, Gao, Han, Zeng, & Yu, 2016) with a differential refractive index detector (Guo et al., 2018).

2.7. Chain length distribution of amylopectin

The branch chain length distribution of amylopectin was measured by high-performance anion exchange chromatography (Dionex ICS-5000, Thermo Scientific, Waltham, MA, USA). The elution gradient was made with 500 mM sodium acetate in 150 mM NaOH against 150 mM NaOH as follows: 0%–20% for 0–5 min, 20%–45% for 5–15 min, 45%–60% for 15–40 min, 60%–70% for 40–65 min, and 70%–100% for 65–80 min. The flow rate was 0.5 mL/min.

2.8. Crystalline structure

Crystalline structure was studied using the method described by Gao et al. (2016) using D8 X-ray diffraction (Bruker, Falkenried, Germany).

2.9. Starch paste properties

The swelling power and water solubility of the starches were determined from 50 to 95 °C in an increment of 5 °C using the method described by Uarrota et al. (2013).

First, 1% starch paste was heated in boiled water for 20 min and then cooled at room temperature for 30 min; light transmittance was obtained at 620 nm by using a spectrophotometer (Blue Star B, Lab Tech Ltd, China).

The freeze–thaw stability of starch was measured by the method of Arunyanart and Charoenrein (2008).

0.25 g of starch and 25 mL of H_2O were mixed in a graduated glass test tube and then placed in a 100 °C water bath for 15 min. Then, the tube was placed at 30 °C and the volume of the supernatant was recorded every 2 h. Retrogradation was measured as the percentage change in supernatant volume with time.

2.10. Thermal properties of starch

Three milligrams of starch was added to 6 μL of water and mixed well. Then, the mixture was sealed and equilibrated in an aluminum pan for 2 h at room temperature. Finally, the sample was heated to 110 °C at a rate of 10 °C/min using a differential scanning calorimeter (Q 2000, TA Instruments, Wood Dale, IL, America) (Gao et al., 2016).

2.11. Pasting property analysis of starch

Pasting properties of starches were measured by using a rapid visco analyzer (RVA 4500, Perten, Sweden). Each sample (3 g) was mixed with water (25 mL) and heated to 50 °C for 1 min and then heated at 12 °C/min to 95 °C. The samples were held at 90 °C for 2 min, cooled at 12 °C/min, and then held at 50 °C for 1 min.

2.12. Statistical analysis

Data were subjected to one-way analysis of variance, Tukey's multiple-comparison analysis, principal component analysis, and Pearson correlation using SPSS 16.0 (IBM Corp., Armonk, NY, USA).

3. Results and discussion

3.1. Chemical analysis

The contents of fat, protein, starch, and amylose of flours and isolated starches are summarized in Supplementary Material Table 1. Fat and protein contents of flours ranged from 0.71% to 3.36% and from 10.03% to 23.85%, respectively. The protein contents of mungbean and pea were significantly higher ($p < 0.05$) than those of the other flours. Some studies have reported that mungbean and pea (Wang et al., 2011) have 20% to 30% protein and are sources of high-quality protein. Therefore, it may be possible to develop a production line that extracts protein and then further extracts starch from mungbean and pea. The flours of sorghum, tartary buckwheat, common buckwheat, mungbean, and pea contained 79.91%, 73.25%, 72.15%, 58.24%, and 61.26% starch, and 4.54%, 23.09%, 31.41%, 33.05%, and 36.31% amylose starch, respectively, which was consistent with results reported by other groups (Hoover & Ratnayake, 2002; Skrabanja et al., 2004; Wang et al., 2011). The five coarse grains all had high starch contents, indicating they were ideal starch sources. The total starch and amylose contents of isolated starch ranged from 96.81% to 98.33% and 5.23% to 65.24%, respectively. The fact that the fat and protein contents of the isolated starches were very low demonstrated the high purity of the isolated starches.

3.2. Morphology and size of starch granules

The morphology and size of granules can greatly affect the physicochemical and rheological properties and even the nutritional function of starch. Starch granules were observed by scanning electron microscopy (Fig. 1). The starch granules of sorghum, tartary buckwheat, and common buckwheat remained structurally intact and showed various shapes (i.e., round, polygonal, or regular) but the size of sorghum starch granules (4–20 μm) was greater than that of buckwheat starch granules (3–10 μm). Most of the starch granules of mungbean and pea had similar elliptical shapes, and a few round granules were observed; starch granule sizes were 10–20 and 10–25 μm, respectively, in mungbean and pea. The shape of starch granules was in agreement with previous reports but the sizes were slightly different from those previously reported (Cai et al., 2014; Kim et al., 2018; Zhu, 2014, 2016), which may be due to differences in genotype backgrounds, environmental factors (Gu, Yao, Li, & Chen, 2013), starch extraction methods (Daiuto, Cereda, Sarmento, & Vilpoux, 2005), and so on. The size of starch granules was measured by a laser diffraction instrument (Fig. 1). Sorghum, mungbean, and pea starches showed unimodal size distributions, whereas the two types of buckwheat showed bimodal size distributions. The median diameter (Supplementary Material Table 1) and the peak diameter (Fig. 1) showed that common buckwheat and pea starches had the minimum and maximum granules sizes, respectively, among the five crops, which was consistent with the scanning electron microscopy results.

The granules of sorghum, tartary buckwheat, and common buckwheat starches were dark at the center and presented the typical “Maltese cross”, whereas starch granules of mungbean and pea had different birefringence patterns at two intersecting lines under polarized light. Starch granules are a type of crystal ball, and the directionality of internal crystal structure (Ambigaipalan et al., 2011) results in appearance of “Maltese cross”. Among the five starch species, the different patterns of “Maltese cross” may have been caused by different positions, shapes, and quantities of the hilum in the granules (Cai et al., 2014).

In addition to image analysis and laser light scattering analysis, flow cytometry is widely considered an effective method for classification of granules. So far, this method has only been used in corn starch (Zhang, Feng et al., 2018). We analyzed plots of forward-scattered light (FSC) versus side-scattered light (SSC) and 1-aminopyrene-3,6,8-trisulfonic acid (APTS) versus SSC, and obtained a histogram of unstained and APTS-stained starches in order to evaluate characteristics of the starch granules (Fig. 2). Of these, SSC, FSC, and APTS, respectively, represented integral structure complexity, granule size, and fluorescence intensity. The histogram of unstained and APTS-stained starches verified the authenticity of the results. The results showed that these five starches can be divided into three types: (1) sorghum starch; (2) tartray buckwheat and common buckwheat starches; and (3) mungbean and pea starches, which might be related to the crop species. Compare with mungbean starch (L1 = 36.7), pea starch (L1 = 71.0) contained larger and more complex granules. No starch granules of buckwheat were observed in the top-right area of the FSC-SSC image, which indicated that buckwheat starch granules were smaller and simpler than other starch granules. The results demonstrated that flow cytometry can be used as a new method to classify starch granules.

3.3. Molecular weight distribution of starch

The *Mw* and gyration radius (*Rz*) of starches ranged from 7.7×10^7 to 19.5×10^7 g/mol and 134.6 to 298.9 nm, respectively (Table 1). Shin et al. (2010) reported that the *Mw* and *Rz* of rice and potato starches ranged from 2.5×10^7 to 10.9×10^7 g/mol and 120 to 214 nm, respectively. The *Mw* and *Rz* of rice starches were reported to be 2.5×10^7 to 10.9×10^7 g/mol and 120 to 214 nm, respectively, by Zeng et al. (2016). The density (ρ) of starches in the current study ranged from 7.3 to 31.4 g/mol/nm^3 (Table 1). In rice and potato starches, ρ ranged from 5.32 to 18.18 g/mol/nm^3 (Shin et al., 2010). The difference between our results and those of Shin et al. (2010) might have been due to the different methods and materials. The *Mw* of sorghum starch was greater than that of other starches, which may be because it had the highest amylopectin content. Generally, the *Mw* of amylopectin is higher than that of amylose (Huang et al., 2015; Shin et al., 2010). Shin et al. (2009) indicated that amylose had a higher *Rz* than amylopectin because amylose has a linear structure and amylopectin has a branched structure. However, in this study, the highest amylose content was found in pea starch, which also had the smallest *Rz*. This inconsistency with the previous study is because *Rz* is likely to be affected by the molecular conformation of amylose and amylopectin.

3.4. Chain length distribution of amylopectin

The physicochemical properties of starch can be greatly affected by the amylopectin chain length (Kim et al., 2018). The distribution of branch chain length of amylopectin is presented in Table 1 and Fig. 3A. Amylopectin branch chains are generally classified into the following types according to their degree of polymerization (DP): B1 chain, B2 chain, and B3 + chains (Ma, Wang, Wang, Jane, & Du, 2017). The average branch chain length, DP 6–12, 13–24, 25–36, and DP ≥ 37 of starches were 21.2%–23.5%, 13.8%–23.4%, 48.5%–51.8%, 16.1%–20.1%, and 11.4%–15.0%, respectively. Pea starch had the highest amylose content and the lowest *Mw*. Pea starch also had the smallest proportion of DP 6–12 and the largest proportion of DP 13–24, DP 25–36, and average branch chain length of amylopectin. Some studies in sorghum (Zhu, 2014) and legume starches (Kim et al., 2018;

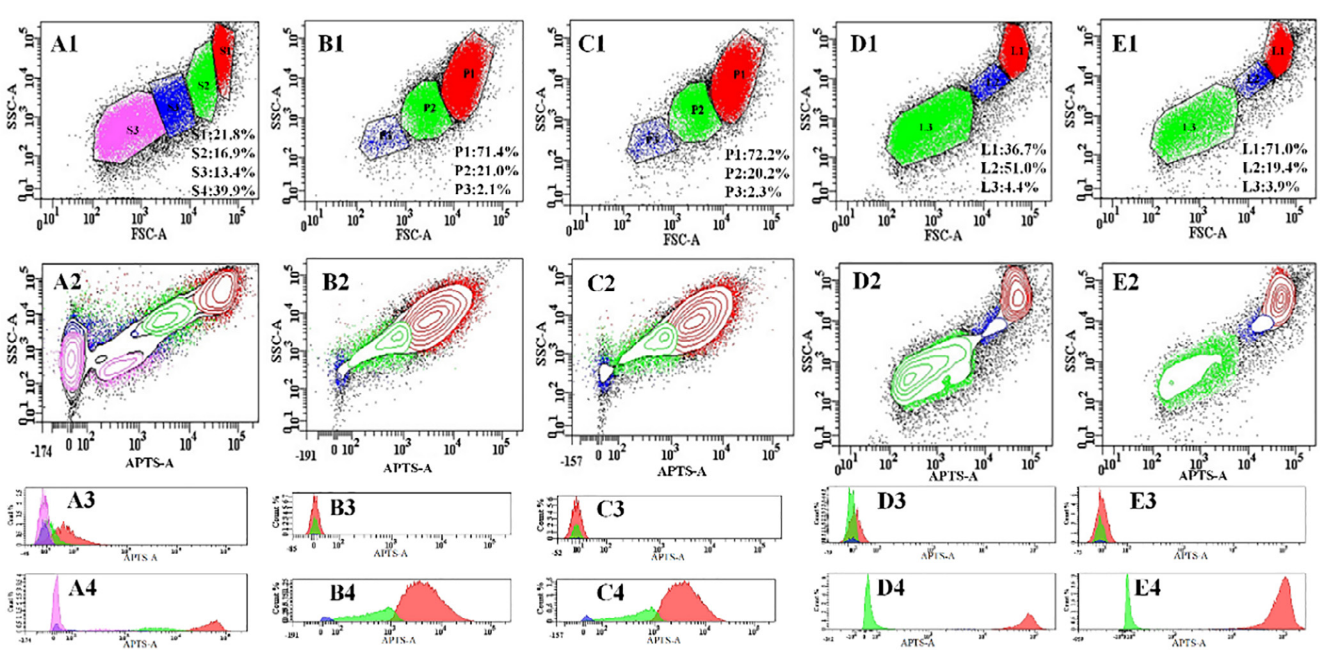

Fig. 2. Bivariate flow cytometric histograms of five starches: (A) sorghum starch; (B) tartary buckwheat starch; (C) common buckwheat starch; (D) mungbean starch; and (E) pea starch. (1) Forward scattered-side scattered (ASC-SSC) image; (2) fluorescence image; (3) histogram of unstained starch (negative control); and (4) histogram of 1-aminopyrene-3,6,8-trisulfonic acid (APTS) stained starch.

Table 1
Weight-average molar mass (*Mw*), average radius of gyration (*Rz*), density (ρ; *Mw/Rz*[3]), amylopectin chain length distribution, and relative crystallinity of starches.

	Mw (×10⁷, g/mol)	*Rz* (nm)	ρ (g/mol/nm³)	Chain length distribution (%)				Average chain length of amylopectin (%)	Relative crystallinity (%)
				DP 6–12	DP13–24	DP 25–36	DP ≥ 37		
Sorghum	19.5 ± 0.2a	298.8 ± 0.8a	7.3 ± 0.2c	18.5 ± 1.4b	51.0 ± 0.3a	17.8 ± 0.3b	12.7 ± 0.2c	22.2 ± 0.6ab	32.9 ± 0.3a
Tartary buckwheat	9.0 ± 0.2c	215.3 ± 1.0d	9.0 ± 0.3b	19.5 ± 1.1b	50.3 ± 1.3ab	16.1 ± 0.2c	14.1 ± 0.1b	22.3 ± 0.4ab	26.0 ± 0.4c
Common buckwheat	10.7 ± 0.6b	243.4 ± 0.8b	7.4 ± 0.3c	20.6 ± 1.0b	48.9 ± 0.1b	15.4 ± 0.3d	15.0 ± 0.2a	22.5 ± 0.8ab	30.9 ± 1.4ab
Mungbean	10.6 ± 0.4b	227.3 ± 2.5c	9.0 ± 0.6b	23.4 ± 0.6a	48.5 ± 0.3b	16.1 ± 0.3c	11.4 ± 0.2d	21.2 ± 0.2b	26.2 ± 0.8c
Pea	7.7 ± 0.2d	134.6 ± 0.6e	31.4 ± 0.4a	13.8 ± 0.6c	51.8 ± 0.6a	20.1 ± 0.1a	14.4 ± 0.4b	23.5 ± 0.5a	28.2 ± 1.7bc

Data represent means ± standard deviations. For each column, values not displaying the same letter are significantly different ($p < 0.05$).
DP, degree of polymerization.

Ma et al., 2017) have reported the chain length distribution of amylopectin, and our results differ from those, perhaps because of differences in materials and methods.

3.5. Crystalline structure

Fig. 3B shows the X-ray diffraction diagram of the starches. The starches of sorghum, tartary buckwheat, and common buckwheat showed the "A" type pattern with diffraction peaks at approximately 15° and 23° 2θ and a continuous double peak at approximately 17° and 18° 2θ, which was consistent with the results in other studies (Cruz et al., 2015; Gao et al., 2016). In addition to these four diffraction peaks, mungbean and pea starches had a weaker peak at 5.6° 2θ, indicating that these two starches presented "C" type pattern. In addition, mungbean had an obvious peak at 18° 2θ, whereas pea had a very weak peak at 18° 2θ, indicating that mengbean showed "Ca" type patterns and pea showed "Cb" patterns (Liu, Wang, Copeland, & Wang, 2015). The relative crystallinity was 32.9%, 26.0%, 30.9%, 26.2%, and 28.2% for sorghum, tartary buckwheat, common buckwheat, mungbean, and pea, respectively (Table 1). Crystallinity was affected by many factors, one of which was amylopectin. Sorghum starch had the highest amylopectin content and highest relative crystallinity. Mungbean starch had the lowest amylopectin content and the chain length of amylopectin was mostly distributed at DP 6–12, which is associated with lower relative crystallinity (Kim et al., 2018).

3.6. Properties of the starch paste

Similar trends of water solubility and swelling power were observed in these five starches (Fig. 3C, 3D). Water solubility and swelling power initially increased slowly and then increased more quickly as the temperature increased. The water solubility and swelling power of common buckwheat starch increased after 60 °C, and those of sorghum, tartary buckwheat, mungbean, and pea starches increased after 65 °C. The water solubility of starches at 95 °C ranged from 15.3% to 53.9% and swelling power ranged from 13.8 to 24.5 g/g. Both properties are affected by many factors, the most important of which are amylose and amylopectin (Huang et al., 2015). Amylose can inhibit the swelling of starch grains (Cai et al., 2014). In the current study, sorghum starch had the highest water solubility and swelling power, whereas pea starch had the lowest.

Starch undergoes chain breaking when it is mixed and heated with

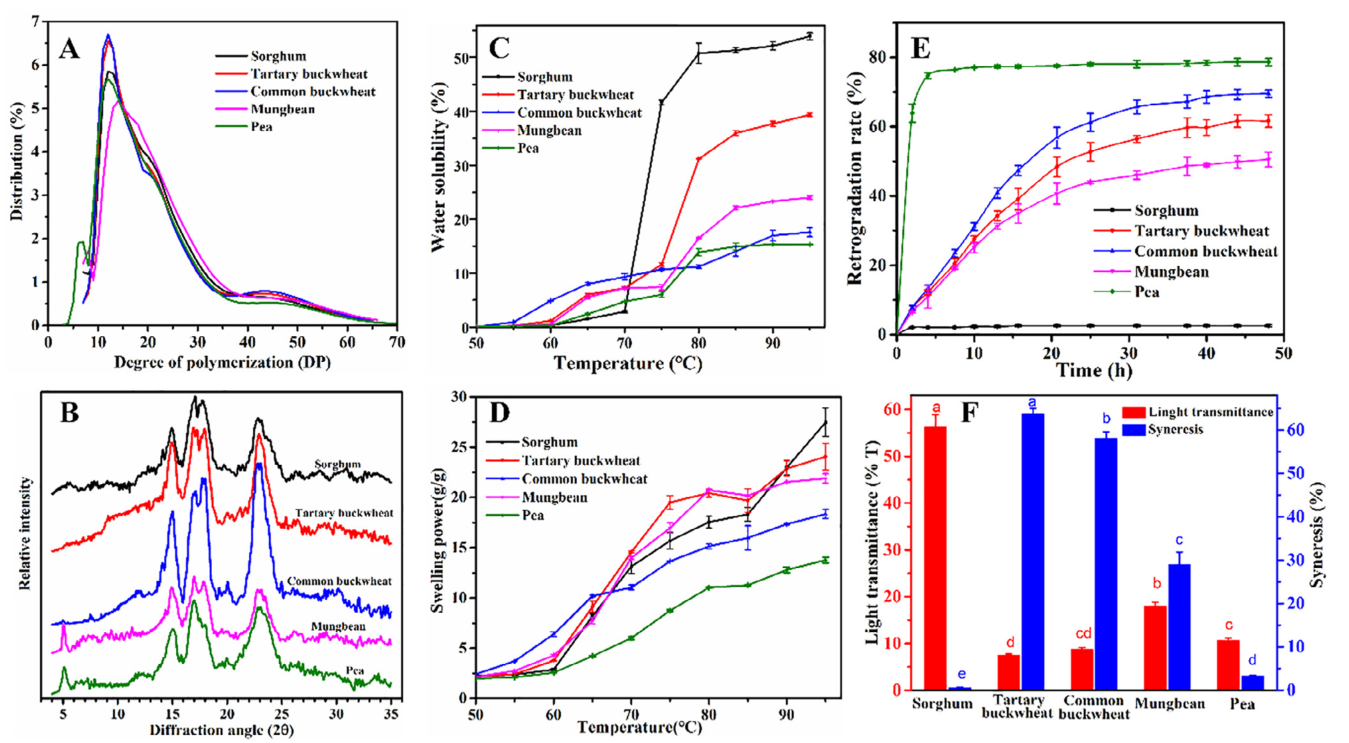

Fig. 3. Properties of starch structure (A, B) and starch paste (C–F): (A) amylopectin chain length distribution; (B) X-ray diffraction patterns of starches; (C) water solubility of starch; (D) swelling power of starch; (E) retrogradation of starch; and (F) light transmittance and freeze–thaw stability of starch.

water, and the interrupted starch chains then recombine during the subsequent cooling, a process termed "retrogradation" (Wang, Li, Copeland, Niu, & Wang, 2015). The retrogradation rate of starch is illustrated in Fig. 3E. The retrogradation rates of sorghum and pea starch pastes increased rapidly during the first 4 h and then stabilized; sorghum starch had the lowest retrogradation rate (2.56%) and pea starch had the highest rate (78.64%). The retrogradation rates of tartary buckwheat, common buckwheat, and mungbean were 69.51%, 61.60% and 50.52%, respectively, and these starches stabilized after 30 h. Compared with amylopectin, amylose is more likely to initiate retrogradation of starch at a size range of 14–24 (Wang et al., 2015). Although the amylose content of mungbean starch was higher than that of the buckwheat starches, the retrogradation rate of mungbean starch was lower, probably because mungbean starch contained more short amylopectin (DP 6–12 = 23.4%) (Wang et al., 2015).

The results of transmittance (%T) of starches are presented in Fig. 3F. Sorghum starch showed the highest light transmittance (56.33%) and its amylose content was extremely low, which was consistent with previous studies indicating that an increase in amylose content will reduce transparency of starch paste (Chao et al., 2014). Compared with the other starches, common buckwheat (8.85%) and tartary buckwheat (7.56%) starches had lower light transmittance, which could be attributed to their smaller particle size and wider particle distribution (Liu et al., 2015). Freeze–thaw stability is an important property that is used to evaluate the ability of starch to withstand the undesirable physical changes that may occur during freezing and thawing. Good freeze–thaw stability is essential for starch-based frozen convenience foods. We assessed freeze–thaw stabilities of starch by the syneresis rate, and the lower the syneresis rate, the better the freeze–thaw stability. In these five starch pastes, the syneresis rate ranged from 0.16% to 63.74% with sorghum starch having the lowest and tartary buckwheat starch the highest (Fig. 3F). The syneresis rates of common buckwheat, mungbean, and pea were 58.19%, 29.07%, and 3.37%, respectively. Sorghum starch had better freeze–thaw stability (i.e., the lowest syneresis rate) because it had the lowest amylose content, which was consistent with other studies showing that amylose content is negatively correlated with freeze–thaw stability (Arunyanart & Charoenrein, 2008). These results showed that sorghum starch has good stability. Both tartary buckwheat and common buckwheat starches showed poor freeze–thaw stability, which may be associated with their genetic background. Also, changing the freeze–thaw conditions; for example, by adding NaCl, saccharose or hydrophilic colloid, could improve the freeze–thaw stability of starch (Arunyanart & Charoenrein, 2008).

3.7. Thermal properties of starch

The onset (To), peak (Tp), and completion (Tc) temperatures of gelatinization and the gelatinization enthalpy (Δ*H*) ranged from 60.6 to 67.0 °C, 67.0 to 71.8 °C, 73.7 to 78.0 °C, and 6.0 to 10.3 J/g, respectively (Table 2). A higher gelatinization temperature means more perfect crystal structure (Kim et al., 2018). Gelatinization enthalpy is the energy needed to melt of starch granules (Gao et al., 2016). Sorghum starch had the highest To, Tp, Tc, and Δ*H* and the highest degree of crystallinity among the five starches in our study. The Δ*H* values of mungbean and pea were lower than those of the other starches, which may be caused by crystal types or granule shapes.

3.8. Pasting properties of starch

The pasting properties of starches are presented in Table 2. Pasting temperature (PTM) and peak time (PT) ranged from 73.6 to 78.1 °C and from 3.8 to 4.9 min, respectively. Higher PTM and PT values indicate that starch is more difficult to gelatinize. Peak viscosity (PV) ranged from 3221 to 7176 cP, with pea starch having the highest PV and common buckwheat starch the lowest. Trough viscosity (TV) ranged

Table 2
Pasting and thermal properties of starches.

	Pasting properties							Thermal properties			
	PV (cP)	TV (cP)	BD (cP)	FV (cP)	SB (cP)	PTM (°C)	PT (min)	To (°C)	Tp (°C)	Tc (°C)	ΔH (J/g)
Sorghum	4503 ± 114b	1433 ± 21d	3070 ± 93b	2195 ± 13d	762 ± 35d	75.5 ± 0.6b	3.8 ± 0.1d	67.0 ± 0.3a	71.8 ± 0.3a	78.0 ± 0.8a	10.3 ± 0.8a
Tartary buckwheat	4166 ± 22c	2397 ± 22b	1769 ± 44c	4396 ± 25b	1999 ± 47b	73.6 ± 0.0c	4.0 ± 0.1c	64.7 ± 0.4b	69.1 ± 0.1b	75.4 ± 1.3b	8.6 ± 0.0b
Common buckwheat	3875 ± 52d	2267 ± 44c	1608 ± 8d	4212 ± 62c	1945 ± 18b	74.3 ± 0.0c	4.3 ± 0.0b	63.6 ± 0.1b	68.9 ± 0.1b	75.3 ± 0.1b	10.1 ± 0.3a
Mungbean	7176 ± 91a	3391 ± 54a	3786 ± 36a	4432 ± 134b	1059 ± 37c	73.6 ± 0.0c	4.2 ± 0.0b	60.6 ± 0.6c	67.0 ± 0.1c	73.7 ± 0.9b	7.4 ± 0.1c
Pea	3221 ± 69e	2286 ± 37c	935 ± 33e	4990 ± 35a	2704 ± 2a	78.1 ± 0.5a	4.9 ± 0.0a	63.5 ± 0.7b	68.9 ± 0.3b	74.9 ± 0.2b	6.1 ± 0.2d

Data represent means ± standard deviations. For each column, values not displaying the same letter are significantly different ($p < 0.05$).
PV, peak viscosity; TV, trough viscosity; BD, breakdown viscosity; FV, final viscosity; SB, setback viscosity; PTM, Pasting temperature; PT, peak time.
To, onset temperature; Tp, peak temperature; Tc, conclusion temperature; ΔH, gelatinization enthalpy.

from 1433 to 3391 cP, with mungbean starch having the highest TV and sorghum starch the lowest. Breakdown (BD) is an indicator of the degree of granule disintegration and reflects the heat resistance of the starch; lower BD indicates stronger heat resistance (Zhang, Zhao et al., 2018). Breakdown ranged from 935 to 3786 cP, with mungbean starch having the highest BD and pea starch the lowest. The highest PT and PTM and the lowest PV and BD in pea starch indicated strong cohesion and high thermal stability in the starch granules. In contrast, PV, TV, and BD of mungbean starch were the highest of the five starches. Final viscosity (FV) and setback (SB) ranged from 2195 to 4990 cP and from 762 to 2704 cP, respectively. High FV and SB indicate poor stability and a tendency to retrograde (Gao et al., 2016). Pea starch had the highest FV and SB, and sorghum starch had the lowest. This result indicated that sorghum starch had good stability and could resist retrogradation, consisted with the results for retrogradation rate (Fig. 3E) and freeze–thaw stability (Fig. 3F). Mungbean starch exhibited special pasting properties, which was consistent with its starch paste properties.

3.9. Principal components analysis (PCA) and correlation analysis

PCA and correlation analysis were carried out in this study to better understand the characteristics of these starches (Fig. 4). PC1 and PC2 accounted for 45.93% and 35.91% of the total variance, respectively. Tartary buckwheat and common buckwheat starches were the closest, indicating that their starches had similar properties. The main contributors corresponding to sorghum starch were Tc and To, and the main contributors corresponding to mungbean starch were TV and starch content. The amylose content was highly negatively correlated with *Mw*, *Rz*, To, and Tc, and positively correlated with FV and PT ($p < 0.05$). Furthermore, amylose content was highly negatively correlated with *Mw*, *Rz*, To, and Tc, and positively correlated with FV and PT ($p < 0.05$).

4. Conclusion

We studied structural and physicochemical properties of starches from five coarse grains. Although all five starches showed the typical "Maltese cross" effect (birefringence), they differed significantly in granule morphology, size, and complexity. Sorghum starch had the lowest amylose content but the highest *Mw*. Mungbean starch contained more short amylopectin (DP 6–12 = 23.4%). Pea starch had the highest amylose content and amylopectin average chain length, but the lowest *Mw*. The starches of sorghum, tartary buckwheat, and common buckwheat showed A-type crystallinity, whereas mungbean and pea starches showed C-type crystallinity. Sorghum starch had good stability and is suitable for use as a frozen food additive or food thickener. Tartary buckwheat and mungbean starches are good ingredients for making jelly because of their moderate retrogradation rate and swelling power. Pea and common buckwheat starches had high retrogradation rates and are suitable for making vermicelli. In addition, pea starch had the best transparency and would be a good additive for making medicine. Our results provide valuable information for the application of starches of

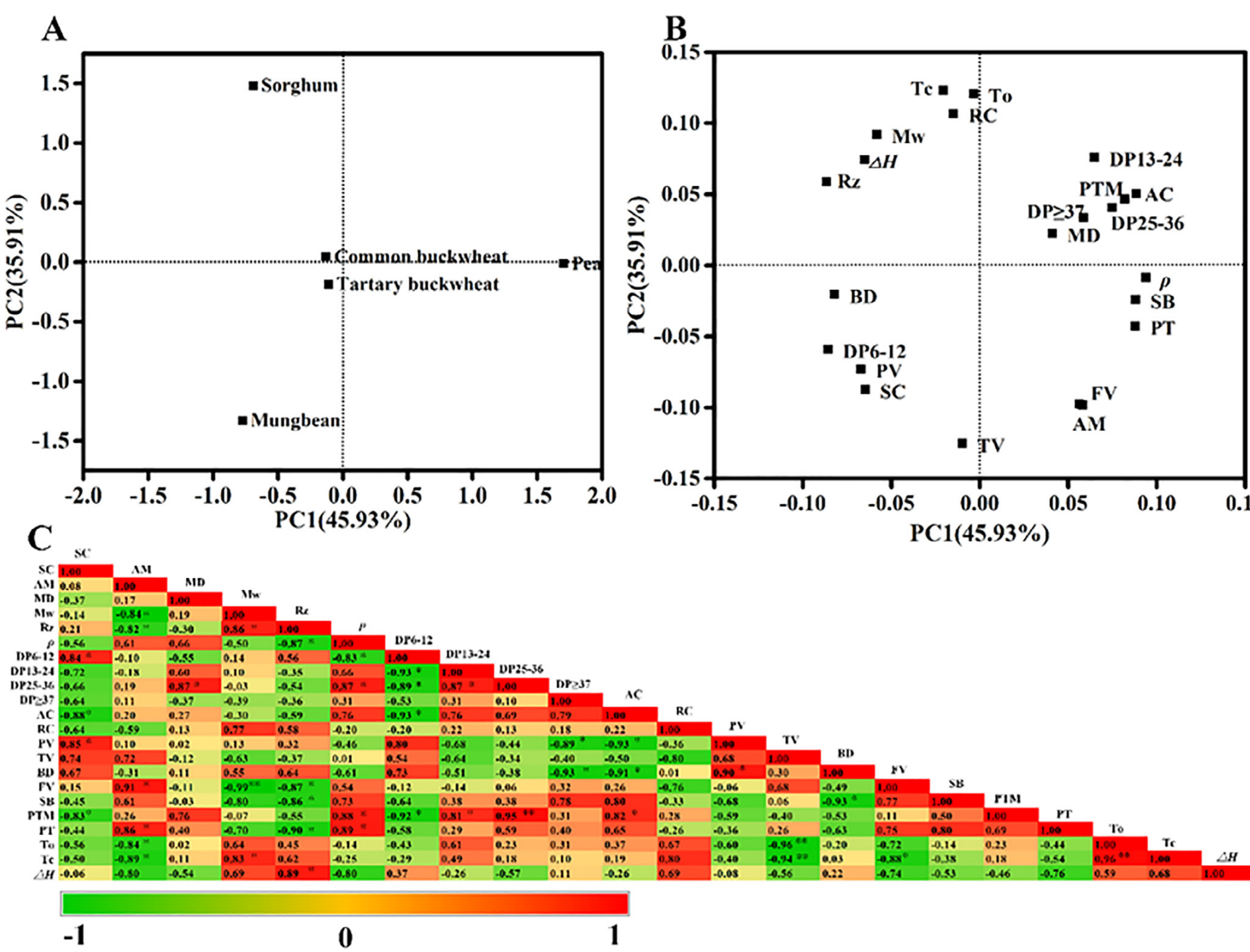

Fig. 4. Principal components analysis score (A) and loading plot (B) of structural and physicochemical properties for five starches showing the first two principal components. (C) Pearson's correlation coefficients between structural and physicochemical properties of the starch samples. SC, starch content; AM, amylose starch content; MD, median diameter; AC, average chain length of amylopectin; RC, relative crystallinity.

coarse grains in food and nonfood industries.

Conflict of interest

There are no conflicts of interest regarding this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2019.02.134.

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