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Functional and physicochemical properties of flours and starches from different tuber crops

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Flours and isolated starches from different potato and sweet potato varieties were evaluated for their physical, functional, pasting, and thermal properties. The flours had higher protein and amylose contents than starches. The *L* values of the starches ranged from 91.92 (S-2) to 96.42 (S-1); thus, the whiteness of the starch samples was satisfactory. X-ray diffraction mode showed that potato starch could be a special material for crystalline nanomaterials with potential industrial applications. The starches had higher viscosity than flours. Therefore, starches can be used as thickeners in different food products. The flours exhibited high gelatinization temperatures but low enthalpy, which can be attributed to the effects of non-starch components in the flours, such as proteins and lipids. Potato flours and starches exhibited higher amylose contents and pasting characteristics and wider applications in the food industry than sweet potato flours and starches. The purple-fleshed varieties had high antioxidant activity. Therefore, the colorful flours of potatoes and sweet potatoes can be combined with other cereals for the development of functional flours with nutritional applications.

1. Introduction

Potato (*Solanum tuberosum* L.) and sweet potato (*Ipomoea batatas* L.) both belong to the dicotyledonous plants. Potatoes and sweet potatoes are tuber plants with wide adaptability and strong growth ability. They have been recognized as economic crops in many countries [1]. Potato tubers contain carotene and ascorbic acid, which are not found in cereal crops. Potato protein is high in quality and rich in lysine and tryptophan, thereby perfectly matching human nutritional needs [2]. Sweet potato tubers are excellent sources of minerals, such as Ca, Fe, P, K, and Cu. Dietary fibers in the roots of sweet potatoes can also reach 8% [3]. In recent years, researchers have produced colorful potato and sweet potatoes rich in phenolic compounds, such as anthocyanins and carotene. These cultivars may be considered health food because anthocyanin and carotene are popular dietary antioxidants [4]. These nutritional properties show the potential applications of potato and sweet potato flours for functional food formulations, such as fruit desserts or pastries.

Starch is a major source of carbohydrates in the human diet, and has a wide range of applications [5]. Potatoes and sweet potatoes are important starchy tuber crops with starch contents of 66%–80% and 58%–80% of dry matter, respectively. Up to now, potato and sweet potato starches have been widely used in food and industry and are still a research hotspot [6]. Thus, potatoes and sweet potatoes are attractive sources of starch. Wang et al. [7] reported that potato starch, owing to its large granule size, has higher peak and breakdown viscosity and lower pasting temperature than maize and pea starches. Among all starches, potato starch has the largest granules (25–100 μm), and thus its industrial applications superior [7].

Potato and sweet potato are respiration climacteric tuber crops. Approximately 10%–15% of all harvested potatoes and sweet potato cannot be used because they are perishable during storage. Since potatoes and sweet potatoes contain large amounts of starch (over 60% of dry weight) and flours with high nutritional value. Thus, the abundant resources of the flours and starches of potatoes and sweet potatoes can be utilized when their industrial chain is extended and human interest is enhanced. Many natural starches and flours with different functions are available on the market, but the demand for specific starch and flour properties is increasing; thus novel strategies or sources are needed [8]. The suitability of flours and starches for specific requirements and uses requires the understanding of their functions and physicochemical properties [9]. Many studies reported the physical and chemical properties of potato and sweet potato starches [10,11]. However, information on the functional properties of their flours is rare. Understanding the physicochemical properties of flours and starches is critical to determining their potential uses and thermal processes without altering their composition, nutritional, and health properties [12]. Therefore, this

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study aimed to elucidate the structural, physicochemical, and thermal properties of flours and starches from potato and sweet potato varieties and determine whether flours are suitable for the production of specific quality products for specific uses. This work also aimed to provide useful information on the application of flours and starches in food and non-food industries.

2. Materials and methods

2.1. Plant materials

Potato and sweet potato tubers with different flesh colors were used in this study. Three cultivars of potatoes, namely, Xisen 6 (P-1), Hongmei (P-2), and Heimeiren (P-3), were provided by Northwest A&F University. Three cultivars of sweet potato, namely, Yu 15 (S-1), Qin 7 (S-2), and 10-6-5 (S-3), were obtained from Baoji Academy of Agricultural Sciences, Shaanxi, China. Starches and powders from fresh tuber were used as plant materials in this study. Fresh tubers were washed and sliced into small pieces. The sliced pieces were immediately steeped in 2% $C_2H_2O_4$ aqueous solution for 1–2 min, placed in an oven at 105 °C for 2 h, dried at 40 °C, and passed through a 100-mesh sieve. Sweet potato flour extracts were prepared in accordance with the method described by Zhang et al. [13] with slight modifications.

2.2. Determination of antioxidant content

2.2.1. Determination of anthocyanin and total phenolic content

The anthocyanin content of fresh root was determined following the pH differential method [14]. Total phenolic content was determined using Folin–Ciocalteau reagent (FCR) [15]. The absorbance was measured at 765 nm. The total phenolic content was expressed as gallic acid equivalents.

2.2.2. Ferric reducing antioxidant power

Ferric reducing antioxidant power (FRAP) solution [16] was prepared by mixing 300 mM acetate buffer (pH 3.6) and 10 mM 2,4,6-tripyridyl-s-triazine in 40 mM HCl and 20 mM $FeCl_3 \cdot 6H_2O$ in a volume ratio of 10:1:1. The resulting mixture was allowed to stand at 37 °C for 5 min. Then, 100 μL of each extract and 300 μL of H_2O were added to the working solution. The absorbance of the mixture was determined at 593 nm after incubation at 37 °C for 4 min.

2.3. Isolation of potato and sweet potato starches

The potato and sweet potato tubers were washed, peeled, chopped, and homogenized using a home blender. The homogenate was filtered through two layers of 100- and 200-mesh. The filtrate was collected and centrifuged. The sediment was steeped in 0.1% NaOH aqueous solution to settle for 4 h. The supernatant was decanted, and the yellowish layer on the top of the starch was scraped. Then, the starch solution was washed three times with 0.1% NaOH aqueous solution and water, respectively. The precipitated starch was dried in an air-forced oven (40 °C), ground into powder, and passed through a 100-mesh sieve.

2.4. Chemical composition

The protein contents were determined as total nitrogen content in accordance with the Kjeldahl procedure. Amylose contents were determined using an amylose test kit 97 (Megazyme Co., Ltd., Bray, Ireland).

2.5. Color of starches and flours

The colors of the starches and flours were evaluated using a chroma meter (Colorimeter Ci7600, Aisaili Colour Technology Inc., Shanghai) as *L* (lightness), ± a (redness/greenness), and ± b (yellowness/blueness) values.

2.6. Morphological observation and granule size analysis of starch

The starch suspension in 50% glycerol was observed using an Olympus BX53 polarized light microscope (Olympus, Tokyo, Japan) under normal and polarized light. The submicroscopic morphology of the starch was observed with a S-4800 scanning electron microscope following the method described by Yang et al. [17]. The size distribution of starch granules was analyzed using a laser diffraction instrument (Mastersizer 2000, Malvern, England).

2.7. XRD analysis of starches and flours

An X-ray diffractometer (D/Max2550VB+/PC, Rigaku Corporation, Tokyo, Japan) was used in investigating the type of crystal and crystallinity of starches and flours. The starches and flours were exposed to X-ray beam at 100 mA and 40 kV and scanned from 5° to 50° 2θ with a step size of 0.02°.

2.8. Vibrational analysis by ATR-FTIR

The short-range ordered structures of the starches and flours were analyzed using an attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectrometer. The original spectrum was obtained through the deconvolution method. Then, the band intensity ratios of 1045/1022 and 1022/995 cm^{-1} were calculated.

2.9. Textural properties of starches and cooked potatoes and sweet potatoes

In this work, 8% of the starch suspension was heated in a boiling water bath for 30 min and cooled to room temperature. Then, starch milk was placed in a refrigerator at 4 °C for 12 h. The texture characteristics of the starch gel were determined by a TA-XT plus texture analyzer (Stable Micro Systems Ltd., Surrey, UK) at room temperature.

Potato and sweet potato tubers were prepared by washing and cutting the root flesh. The sample was placed in a pot. The tuber was considered cooked when the stainless steel probe could easily penetrate the tuber. Tubers required different cooking times ranging from 30 min to 35 min. The cooked sample was sliced into 20 mm central slices. The textural properties of the cooked potato and sweet potato were measured using the method of Yang et al. [5]

2.10. Thermal properties of starches and flours

Thereafter, 3 mg of sample was accurately weighed in an aluminum pan and added with deionized water (9.0 μL). The mixture was sealed and equilibrated for 2 h at room temperature. The sample was heated at 40–120 °C at a rate of 10 °C/min. An empty pan was used as a reference [18].

2.11. Apparent viscosity measurement

The pasting properties of the starches and powders were analyzed using a rapid visco-analyzer (RVA 4500, Perten, Sweden) following the method of Zhang et al. [19].

2.12. Statistical analysis

All measurements were performed in triplicate and data were analyzed using ANOVA. Significant differences in means were established at $p \leq 0.05$. The results were presented as means ± standard deviation.

Table 1
Total anthocyanin and phenolic, antioxidant capacity of sweet potato.[a]

Varieties and lines	Anthocyanin content (mg/100 g fw)	Total phenolic (mg GAE/g dw)	Total antioxidant capacity (FRAP) (μ mol/g dw)
P-1	–	4.57 ± 0.03d	9.99 ± 0.22e
P-2	24.38 ± 0.81c	7.03 ± 0.05c	26.36 ± 0.18c
P-3	57.08 ± 0.14a	10.02 ± 0.41b	40.74 ± 0.16b
S-1	–	1.27 ± 0.13e	13.70 ± 0.17d
S-2	–	5.44 ± 0.19d	27.75 ± 0.64c
S-3	39.42 ± 0.15b	15.25 ± 0.37a	61.44 ± 0.46a

[a] Data are means ± standard deviation, n = 3. Values in the same column with different letters are significantly different ($p < 0.05$).

3. Results and discussion

3.1. Antioxidant profile of potato and sweet potato tuber

The antioxidant profile of potato and sweet potato is shown in Table 1. Purple-fleshed potato had the highest anthocyanin content among the samples. Fig. 1 shows that the color of potato was deeper than that of sweet potato and consistent with the measured anthocyanin results. Only purple- and pink-fleshed sweet potatoes show detectable anthocyanins [4]. However, we did not detect anthocyanins from orange-fleshed varieties possibly due to the varieties tested. Anthocyanin is a natural anti-aging nutritional supplement and the safest and most effective free-radical scavenger identified [20]. Therefore, colored potatoes and sweet potatoes have broad prospects for development in the healthcare industry.

The total phenolic contents ranged from 4.57 mg CAE/g dw to 10.02 mg CAE/g dw among the potatoes and from 1.27 CAE/g dw to 15.25 mg CAE/g dw among the three sweet potatoes. Yoshinaga et al. have reported that the total phenolic contents range from 2 CAE/g dw to 18 mg CAE/g dw among various sweet potato varieties [21]. Although S-3 had higher anthocyanin content than P-3, its total phenol content was still lower than that of the sweet potato due to genetic factors and growing conditions.

FRAP is widely used in evaluating free radical-scavenging activities in many plant extracts. The FRAP radical scavenging activities ranged from 9.99 CAE/g dw to 61.44 mg GAE/g dw. The antioxidant effects of purple-fleshed varieties were five times those of white-fleshed varieties. Many studies reported that purple-fleshed varieties have the highest phenolic content and antioxidant activity [22,23]. The combined presence of acetylated anthocyanins and phenolic acids in purple-fleshed sweet potato varieties may result in a high antioxidant activity [24]. The antioxidant activity of sweet potato was significantly higher than that of potato. The antioxidant capacity of purple-fleshed sweet potatoes is comparable to those of fruits (cherries) and vegetables (cabbage). High total phenol content corresponds to high antioxidant activity (Table 1). Total phenols are often used as indicators of antioxidant activity in fruits, vegetables, and sweet potatoes.

3.2. Amylose and protein content

Table 2 shows the contents of amylose and protein in flours and starch samples. Amylose contents ranged from 21.6% to 24.5% in potato starches and from 24.9% to 32.7% in flour samples. The amylose contents of flour were higher than those of the starches and are in good agreement with those of previous studies [25]. This result might be due to the removal of protein and fat during starch extraction, resulting in an increase in the proportion of starch. Thus, amylose content increased in the samples. Amylose showed the same pattern in sweet potatoes. In the present work, potatoes were found to have higher amylose content than sweet potatoes. Amylose content can affect the physical properties of starch, such as gelatinization temperatures, swelling power, and crystalline structure [26].

The protein contents of starches from potatoes and sweet potatoes ranged from 0.066% to 0.216% and from 0.070% to 0.095%, respectively; thus, isolated starch is relatively pure. Potato flours had significantly higher protein content than sweet potato flours and are suitable for the development of functional products.

3.3. L, a, and b color parameters

Color attributes have a remarkable effect on consumer and food industries. The flours had low *L* values but high a and b values (Supplementary material Table 1). The differences in flour and starch colors are due to the accumulation of anthocyanins and carotene in flours [27]. Pigments as antioxidants can reduce the risk of chronic diseases [28]. The *L* values, indicating whiteness/lightness, of the starches ranged

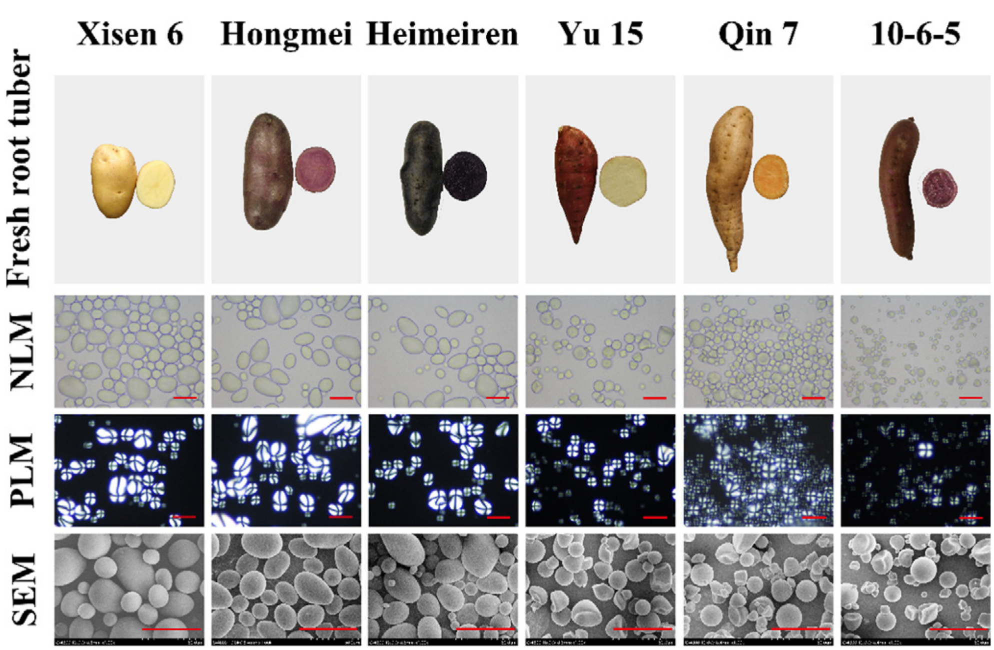

Fig. 1. The photos of potato and sweet potato root tubers, the morphologies of starch granules under normal light microscope (NLM), polarized light microscope (PLM) and scanning electron microscope (SEM), and the granule size distribution of starches. Scale bar = 50 μm.

Table 2
Granule size distribution, amylose and protein of starches and flours.[a]

Varieties and lines	Starches			Amylose (%)		Protein (%)	
	d (0.5)[b]	D [3,2]	D [4,3]	Starches	Flours	Starches	Flours
P-1	36.23 ± 0.15b	33.24 ± 0.19a	39.24 ± 0.01c	21.6 ± 0.5c	24.9 ± 0.6c	0.216 ± 0.030a	9.679 ± 0.128a
P-2	36.90 ± 0.03f	24.51 ± 0.43b	39.92 ± 0.05b	22.7 ± 0.6b	27.4 ± 0.6b	0.066 ± 0.001c	9.414 ± 0.028b
P-3	35.82 ± 0.10a	24.00 ± 0.10c	37.93 ± 0.02d	24.5 ± 0.7a	32.7 ± 0.3a	0.091 ± 0.006bc	8.301 ± 0.104c
Mean	36.32	27.25	39.03	22.93	28.33	0.124	9.131
S-1	26.63 ± 0.03c	23.86 ± 0.04c	35.31 ± 0.01e	18.8 ± 0.8d	23.6 ± 0.8d	0.073 ± 0.013bc	5.473 ± 0.078e
S-2	28.17 ± 0.01e	19.82 ± 0.11d	45.97 ± 0.04a	19.5 ± 0.4d	25.5 ± 0.6c	0.070 ± 0.003bc	5.517 ± 0.141e
S-3	19.58 ± 0.20d	14.20 ± 0.10e	21.84 ± 0.00f	17.7 ± 0.2e	20.9 ± 0.9e	0.095 ± 0.010b	6.946 ± 0.009d
Mean	24.79	19.29	34.37	18.7	23.3	0.079	5.979

[a] Data are means ± standard deviations, n = 3. Values in the same column with different letters are significantly different ($p < 0.05$).
[b] The d (0.5) is the granule size at which 50% of all the granules by volume are smaller. The D (3,2) and D (4,3) are the surface-weighted and volume-weighted mean diameter, respective.

from 91.92 (S-2) to 96.42 (S-1). Boudries et al. [29] considered that the *L* value was higher than 90 and the whiteness of starch is satisfactory. The *L* value of flours ranged from 57.74 to 91.43, with the highest in S-1. Anyasi et al. [30] believe that the addition of flour with high whiteness in the production of food can enhance the nutritional characteristics of food without changing the food color; flour with high whiteness improves the acceptance value of a finished product. Sweet potato flours have higher *L* values than potato flours, and this topic is worth exploring. The results may be due to the difference in tissue composition and structure between potatoes and sweet potatoes. In addition, the a and b values of the starch samples were lower than those of the corresponding flour samples. These results indicate that the main anthocyanins of the pigment and the water-soluble compound can be dissolved in water and removed during starch separation. Although the statistical analysis results were significantly different, the color of the six starch samples were not clearly distinguishable.

3.4. Morphology and granule sizes of starch

The morphology of the potato and sweet potato starches were observed using a polarized light microscope under normal and polarized light and a scanning electron microscope (Fig. 1). The potato and sweet potato starches showed significant difference in morphology. Potato starch had large ellipsoidal granules and small spherical granules with eccentric hila. Most sweet potato starch granules exhibited polygonal, round, semi-oval, and oval shapes and contained small and large granules. A similar morphology in potato and sweet potato starches was reported in previous literature [6,7]. The differences might be attributed to the different biological origins, plant physiologies, and amyloplast biochemistries [31].

Starch granule size was measured using a laser diffraction instrument, and six starches showed different size distributions (Table 2 and Fig. 2). The starch granules of the P-1 and S-1 varieties showed a unimodal distribution. The other four starch granules showed a bimodal distribution with a small population of small granules (1–10 mm). P-2 had the largest granule size, while S-3 had the smallest granule size among the six starch samples. The sweet potato starch has a smaller granule size than potato starches and is consistent with the morphological observation of starch. Sweet potato starches with small granules are suitable as a cosmetic products and paper coating [32].

3.5. X-ray diffraction

The XRD patterns of the studied samples are shown in Fig. 3A and B. The diffraction peaks of flours and starches on sweet potato at 2θ of 15°, 17°, 18°, and 23° were A-type crystals and are in agreement with those reported in literature [3]. The intensities of the reflection of flours were lower than those of their respective starches possibly due to the effects of other components in the flours (proteins, lipids, and crude fibers). The XRD results of potato starches and flours showed the typical C_b type. The peak of potato flours was more obvious than that of the starches. Potato starch granules were larger than sweet potato granules (Table 2) and the granules of other grains [33]. In starch separation, screening and washing large granules may be washed away, resulting in starch loss and a weak diffraction peak forms. The X-ray patterns showed a peak located at a small angle ($2\theta = 5.6°$) for potato starches and flours. Alonso-Gomez, Leonardo et al. [34] reported that the peak appears in fermented cassava starch and explained the origin of this peak and the formation of nanocrystals. This peak has been reported in the starches of potato and pea. Starch morphology might be formed by the semicrystalline contribution of amylose; however, no existing evidence can prove this assumption. The special crystalline structure of potato starch can be determined through calculation and research. It could be a special material of crystalline nanomaterial with future industrial applications.

3.6. ATR-FTIR spectrum

The ATR-FTIR spectra of the flours and starches are shown in Table 3 and Fig. 3C and D. The analysis was concentrated in the region from 900 cm^{-1} to 1200 cm^{-1}, where the most remarkable changes were found. The intensity of absorbance at 1045, 1022, and 995 cm^{-1} was sensitive to changes in starch conformation. The ratio of absorbance 1045/1022 cm^{-1} can be used to quantify the degree of order in the material, and that of 1022/995 cm^{-1} can be used as a measure of the proportion of amorphous to ordered carbohydrate structure in the starch [35]. The other reported bands of the starch are located at 995, 1020,

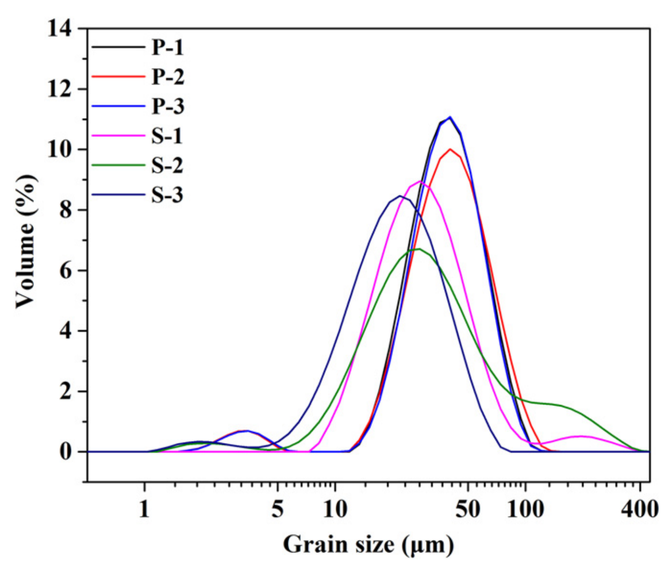

Fig. 2. Grain size distribution of starches.

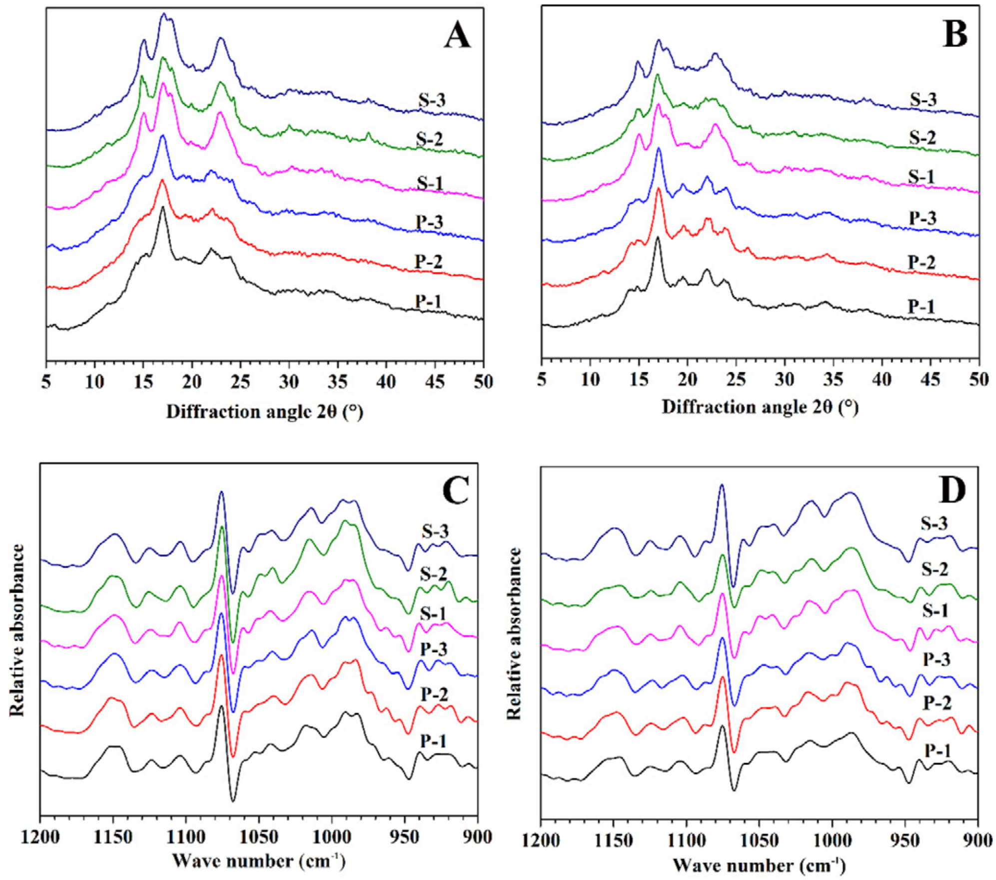

Fig. 3. (A) X-ray diffraction patterns of starches; (B) X-ray diffraction patterns of flours; (C) Ordered structure (FTIR) of starches; (D) Ordered structure (FTIR) of flours.

and 1080 $cm^{-1}$and produced by the C—O, C—C, and C—O—H bending vibrations of the polysaccharide molecules, respectively [36]. A similar spectrum was found in the flours and starches. Potato starches had the lowest ordered degree on the outside of the granules than flours. The same pattern was found in sweet potatoes. The ratio of 1022/995 cm^{-1} of sweet potato flours was lower than that of potato. This phenomenon is attributed to the high protein content of potato flour. The ratios of 1045/1022 cm^{-1} and 1022/995 cm^{-1} in S-1 starch showed significant difference with the other starches, indicating that it had different short-range ordered structures in the starch external region. The ordered structure in the starch external region has a significant effect on pasting viscosity and swelling power [37].

3.7. Textural properties

The hardness of the starch gels ranged from 33.99 g to 114.25 g (Supplementary material Table 2). The hardness of potato starch gels was higher than that of sweet potato. The amylose content can have a remarkable effect on gel hardness as demonstrated by Fu et al. [38]. Amylose plays a role in gel formation as a binding material that links intact or fragmented swollen granules. Table 3 shows that the amylose content of potato is significantly higher than that of sweet potato and is a good indicator of hardness. The high values of adhesiveness were revealed in S-2. High adhesiveness implies soft texture. Thus, S-2 can be used in fruit dessert preparations. The springiness, cohesiveness, and resilience of gel starches ranged from 0.93 to 1.36, from 0.51 to 0.91, and from 0.23 to 0.78, respectively. Thus, P-2 exhibits high value in terms of the above three parameters, suggesting its "rubbery" texture when eaten. Sweet potato gel starch has a lower gumminess value than potato starch. The high gumminess is attributed to a high hardness value, suggesting potato starch is a good additive in confectionery and bakery industries.

The parameters derived from the textural profile analysis for cooked potatoes and sweet potatoes are shown in Table 4. The changes in

Table 3
IR ratio and amylose content of starches and flours.[a]

Varieties and lines	Starches IR ratio		Flours IR ratio	
	1045/1022 cm^{-1}	1022/995 cm^{-1}	1045/1022 cm^{-1}	1022/995 cm^{-1}
P-1	0.314 ± 0.006c	0.715 ± 0.039b	0.469 ± 0.030b	0.716 ± 0.016ab
P-2	0.297 ± 0.014d	0.650 ± 0.017c	0.394 ± 0.038c	0.665 ± 0.028c
P-3	0.296 ± 0.014d	0.650 ± 0.007c	0.390 ± 0.025c	0.723 ± 0.029a
Mean	0.302	0.672	0.418	0.701
S-1	0.363 ± 0.002a	0.726 ± 0.000ab	0.410 ± 0.026c	0.692 ± 0.021abc
S-2	0.316 ± 0.002c	0.700 ± 0.009b	0.533 ± 0.023a	0.675 ± 0.023bc
S-3	0.339 ± 0.008b	0.765 ± 0.040a	0.460 ± 0.005b	0.699 ± 0.023abc
Mean	0.339	0.730	0.468	0.689

[a] Data are means ± standard deviations, n = 3. Values in the same column with different letters are significantly different ($p < 0.05$).

Table 4
Texture profile analysis (TPA) of cooked potato and sweet potato.[a]

Varieties and lines	Hardness	Adhesiveness	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
P-1	247.85 ± 3.82d	208.98 ± 22.26b	1.00 ± 0.01a	0.25 ± 0.00d	62.93 ± 0.91d	62.55 ± 1.48c	0.016 ± 0.003b
P-2	352.00 ± 18.13b	141.50 ± 10.61a	0.96 ± 0.01b	0.19 ± 0.01e	67.55 ± 1.48c	64.82 ± 2.40c	0.022 ± 0.002a
P-3	380.29 ± 19.76a	323.52 ± 15.55d	1.00 ± 0.00a	0.23 ± 0.01d	89.67 ± 1.71b	89.57 ± 1.73b	0.023 ± 0.001a
Mean	326.71	224.67	0.99	0.22	73.38	72.31	0.020
S-1	123.73 ± 4.47f	135.92 ± 13.40a	0.95 ± 0.02b	0.30 ± 0.00c	37.99 ± 1.89f	36.05 ± 2.39e	0.021 ± 0.001a
S-2	151.37 ± 6.64e	253.45 ± 14.62c	1.00 ± 0.00a	0.36 ± 0.02b	55.99 ± 1.40e	55.91 ± 5.01d	0.017 ± 0.001b
S-3	329.16 ± 9.77c	535.75 ± 7.24e	1.00 ± 0.01a	0.41 ± 0.02a	136.43 ± 1.67a	135.45 ± 0.70a	0.023 ± 0.003a
Mean	201.42	308.37	0.98	0.36	76.80	75.80	0.038

[a] Data are means ± standard deviation, n = 3. Values in the same column with different letters are significantly different ($p < 0.05$).

textural characteristics of potatoes during cooking are due to the associated changes in the physicochemical properties and structure components (cell wall and middle lamella) [39]. Table 4 shows that potato samples (P-1, P-2, P-3) have high hardness and adhesiveness attributed to their large starch granules. The cooked potato and sweet potato microstructure has an effect on its textural parameters (Table 4). Cooked sweet potato tuber has higher cohesiveness than the potato tuber because its parenchyma cells remained intact after cooking [40]. The highest textural parameters among the cultivars were observed in S-3, whereas the lowest values were observed from S-1and S-2.

3.8. Thermal properties

The thermal properties of flour and starch samples from potato and sweet potato cultivars are shown in Supplementary material Table 3 and Fig. 4A and B. The gelatinization onset (*T*o), Gelatinization peak (*T*p), gelatinization conclusion (*T*c), and gelatinization enthalpy (*ΔH*) of the potato starches varied from 60.32 °C to 64.81 °C, from 63.90 °C to 68.91 °C, from 74.71 °C to 79.01 °C, and from 12.43 J/g to 13.72 J/g, respectively. *ΔH* of the flours of potato ranged from 9.45 J/g to 10.97 J/g. Thus, starches had lower gelatinization temperatures but higher enthalpy than flours, which could be due to the presence of non-starch components in the flours (protein and lipid); these components require high temperatures to degelatinize [41]. In addition, cell wall material in the flours could also act as a barrier, preventing water from moving toward starch particles and reducing the amount of heat emitted by gelatinization [42]. A similar trend was observed in sweet potato. The gelatinization temperature (*T*c–*T*o) range was the highest in S-2 (18.59 °C). The gelatinization temperature range was wide, indicating the great degree of heterogeneity in the starch crystallites within granules [31].

Sweet potato starches had higher *T*p and *T*c than potato cultivars, representing a high degree of perfect crystalline structure in starches. The gelatinization temperatures are important for selecting ideal varieties with specified physicochemical properties of starches and for various food application requirements [43]. The gelatinization temperatures are affected by amylose content, protein content, granule size, and lipid complexed amylose chains [44]. The gelatinization enthalpy indicates greater loss of double helical structure was found higher in potatoes, which could be impact to the higher amylose content and big granule of potato varieties.

3.9. Pasting properties

The shape of the RVA pasting curves was similar for starch and flour varieties. However, the difference in the pasting curves between potato and sweet potato is significant as shown in Fig. 4C and D. The peak viscosity of starches of potato samples ranged from 7589 cP to 17,439 cP.

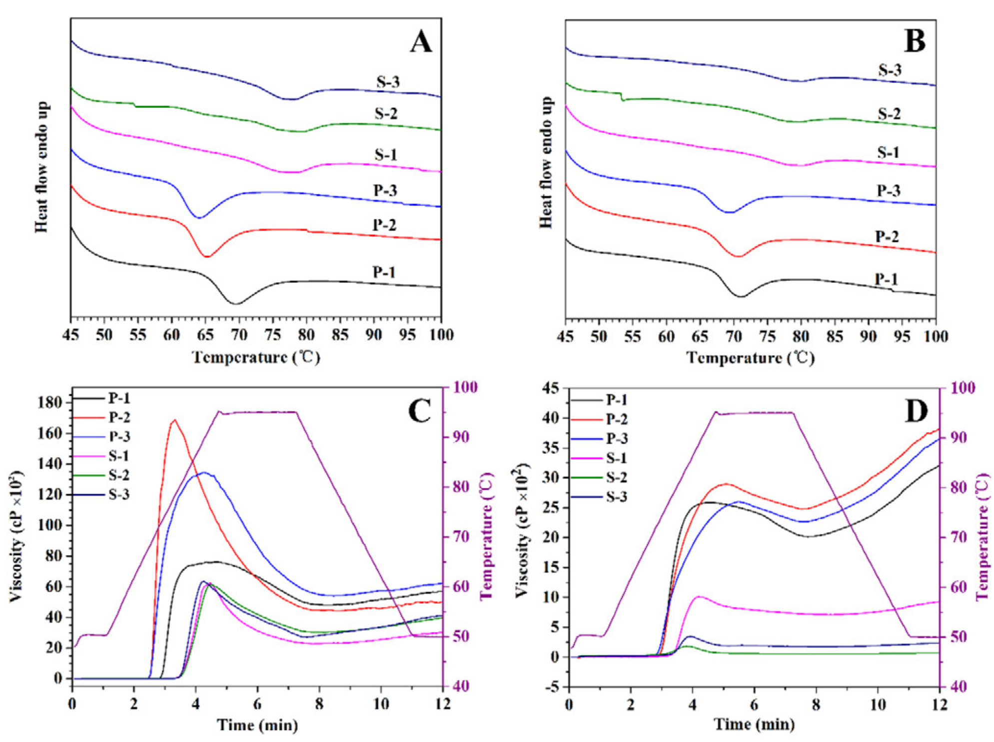

Fig. 4. (A) Thermal property of starches; (B) Thermal property of flours; (C) Pasting properties of starches; (D) Pasting properties of flours.

Table 5
Pasting properties of starches and flours.[a]

Varieties and lines	Starches						Flours					
	PV (cP)	HV (cP)	BV (cP)	FV (cP)	SV (cP)	PT (°C)	PV (cP)	HV (cP)	BV (cP)	FV (cP)	SV(cP)	PT (°C)
P-1	7589 ± 42c	4790 ± 8b	2799 ± 34f	5701 ± 10b	911 ± 19c	72.4 ± 0.4c	2590 ± 5b	2035 ± 17c	555 ± 12a	3393 ± 30c	1357 ± 13c	73.5 ± 0.1c
P-2	17,439 ± 158a	4481 ± 19c	12,957 ± 250a	4928 ± 22c	487 ± 2f	69.1 ± 0.4d	2922 ± 25a	2507 ± 10a	414 ± 2b	4050 ± 50a	1542 ± 22b	73.5 ± 0.1c
P-3	13,659 ± 187b	5579 ± 61a	8079 ± 36b	6375 ± 53a	795 ± 9e	67.9 ± 0.0e	2551 ± 47e	2201 ± 57b	350 ± 4c	3825 ± 32b	1624 ± 23a	72.1 ± 0.5d
Mean	12,895	4950	7945	5668	731	69.8	2688	2248	440	3756	1508	73.0
S-1	6337 ± 68d	2263 ± 12f	4074 ± 81c	3096 ± 53f	833 ± 29d	78.8 ± 0.4b	1009 ± 1d	716 ± 4d	293 ± 4d	992 ± 8d	275 ± 2d	79.2 ± 0.1b
S-2	6112 ± 37e	2918 ± 40d	3193 ± 24e	4046 ± 58e	1127 ± 23b	79.8 ± 0.8a	182 ± 0f	54 ± 1f	127 ± 1f	65 ± 1f	11 ± 0f	79.9 ± 0.1a
S-3	6099 ± 2e	2669 ± 42e	3701 ± 25d	4160 ± 35d	1490 ± 6a	79.2 ± 0.0ab	346 ± 1c	173 ± 0e	172 ± 1e	244 ± 1e	71 ± 1e	79.2 ± 0.1b
Mean	6183	2617	3656	3767	1150	79.3	512	314	197	434	119	79.4

[a] Data are means ± standard deviation, n = 3. Values in the same column with different letters are significantly different ($p < 0.05$).

The starch viscosity of P-2 and P-3 was five times that of the whole flour. The viscosity of flour was mainly produced by starch. Breakdown viscosity is the measurement of the susceptibility of starch to thermal pasting and mechanical shear. The higher the breakdown in viscosity, the lower the ability of the flour samples to withstand shear stress and heating during cooking [45]. Thus, flour potato might be able to

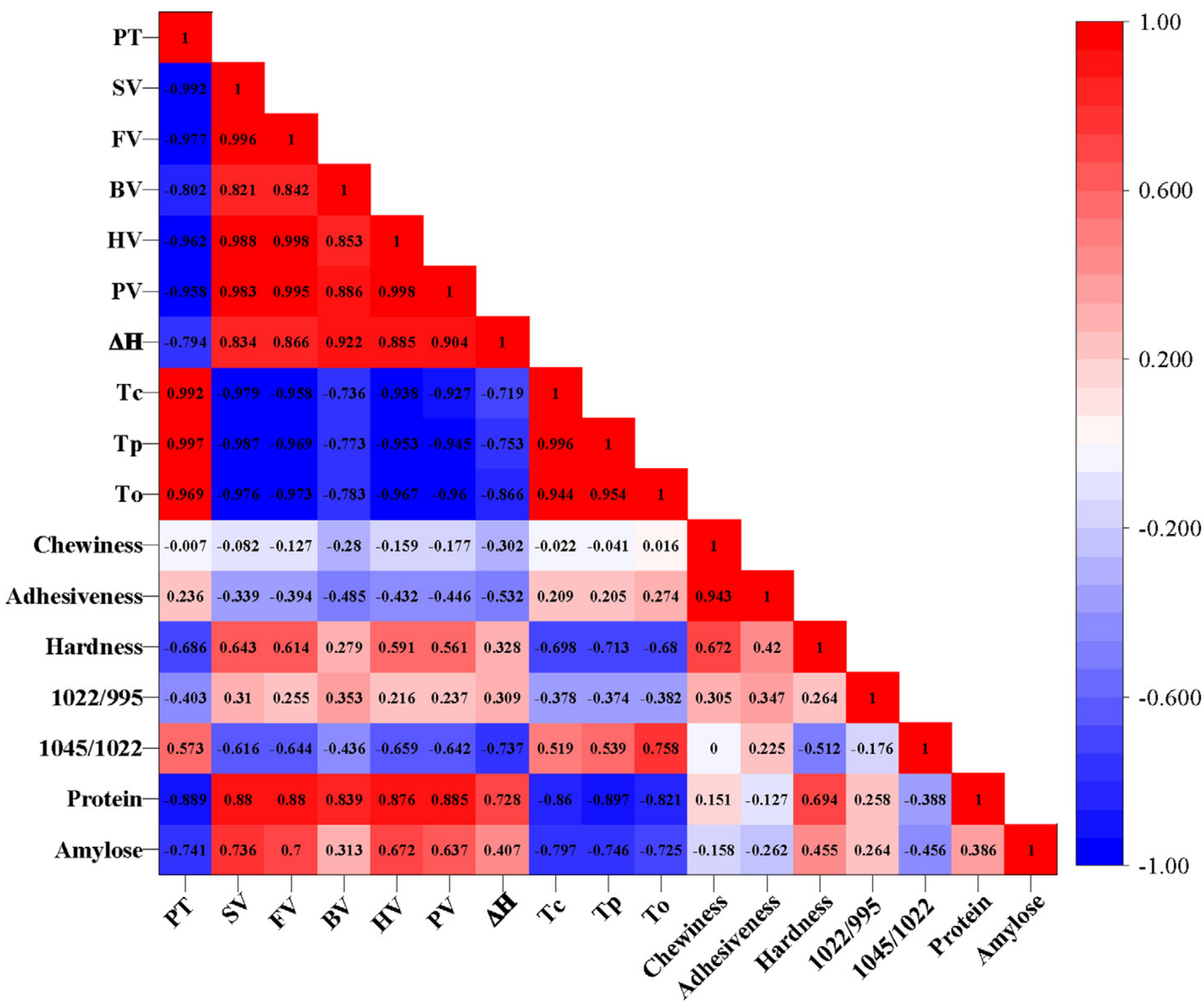

Fig. 5. Pearson's correlation coefficients between structural and physicochemical properties of the flour samples.

withstand higher shear stress and heating temperatures than starches. The setback viscosity of the starches and flours of potato varied from 487 cP (P-2) to 911 cP (P-1) and from 1357 cP (P-1) to 1624 cP (P-3), respectively; thus, flours might have a remarkable tendency to retrograde than starches. The starch paste of potato has a lower pasting temperature than that of flours and is consistent with the DSC results. The thermal characteristics of sweet potato starches showed significant differences among varieties, and flour showed extremely low thermal characteristics. Setback is an important index in the prediction of storage life of product prepared from flour. The S-2 flour had the lowest setback viscosity. Therefore, S-2 flour with lowest setback viscosity might be added to cakes to extend their shelf life. In terms of pasting properties, flour exhibits limited expansion, low breakdown rate, and higher peak temperature during cooling compared with starch. These results are similar with those of a previous study [25]. The pasting properties among flour and isolated starch are different due to the presence of lipid, protein, and fiber in flour, as well as the lower of starch in flour [46]. The amylose content of potato is considerably higher than that of sweet potato, and amylose component determines the structure and pasting behavior of starch granules. Thus, the peak viscosity of potato samples is considerably higher than that of sweet potato. The setback values of the potato starch samples were lower than their flour, whereas the opposite trend was found in sweet potato. This phenomenon may be attributed to the formation of starch–lipid or starch–protein complexes in the flour sample that can increase the setback value [41]. Thus, potato flours containing high amylose content and protein display a higher setback value than starch flours. Sweet potato flour with a low setback value is more resistant to storage than potato flours. The sweet potato paste shows a higher pasting temperature than potato paste. Therefore, the sweet potato raw material has potential applications as a thickener in products that require sterilization, such as seasonings and baby foods [47].

The viscosities of flour and starch show certain pattern characteristics until the peak value. Viscosity decreased at holding and increased to reach the final viscosity (Fig. 4D and C). The starch paste viscosity patterns were classified as types A, B, C, and D [48]. After the peak viscosity was reached, the flours and starches exhibited different patterns of pasting properties, which can be used to predict cooking characteristics and other food utilization characteristics of the variety. P-1 showed a slight shear thinning (Type C), while P-2 and P-3 showed a high pasting peak and high thinning during cooking (Type A). S-1, S-2, and S-3 showed low pasting peak and moderate shear thinning (Type B) behavior (Fig. 4C). The whole powder of all samples is the same type as the starch. Starches and flours did not show Type D behavior. The amount of D-type starch must be increased by two to three times to obtain a significant C-type hot paste viscosity of [49].

3.10. Correlation analysis

A heat map was constructed to further elucidate the relationship among amylose contents, protein contents, and the structure, thermal, and pasting properties of flours. Amylose content had a significant positive correlation with SV, FV, BV, and PV, whereas a negative correlation was found among Tp, Tc, and To in the flour samples (Table 5). Similar relationships were found between protein content and thermal properties and the pasting properties of flour samples. Non-starch ingredients, such as protein, have a considerable effect on flour characteristics. The chewiness was highly positively correlated with adhesiveness and hardness (Fig. 5).

4. Conclusions

In this study, the flours exhibit higher protein and amylose content than those of starches. The potato starch showed varied granule size from 35.82 μm to 36.90 μm. According to X-ray diffraction, potato starch granule may have a special crystal structure. The cooked tuber of sweet potato varieties differed from those of others in terms of decreased hardness and chewiness with satisfactory palatability. The components (fat and protein) of flour could affect their physicochemical properties, especially their viscosity. Viscosity developed from starch that had higher viscosity value than the flour, especially potato starch with higher viscosity. Therefore, starch could be used as a thickener in different types of food formulations. Colored potatoes and sweet potato have a strong antioxidant capacity and high nutritional content. Their flours could be combined with other grains to develop functional flours for nutrimental applications.

Declaration of competing 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.ijbiomac.2020.01.146.

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