International Journal of Biological Macromolecules 160 (2020) 660–668

Contents lists available at ScienceDirect

International Journal of Biological Macromolecules

journal homepage: http://www.elsevier.com/locate/ijbiomac

Isolation and characterization of starch from light yellow, orange, and purple sweet potatoes

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ARTICLE INFO

Article history:
Received 24 February 2020
Received in revised form 27 May 2020
Accepted 28 May 2020
Available online 01 June 2020

Keywords:
Sweet potato
Starch
Amylose

ABSTRACT

Sweet potato is attracting increased research attention because of its high nutritional value (e.g., carotene, anthocyanin, and minerals) and the wide application of its starch in foods and nonfoods. Herein, eight Chinese sweet potato varieties were investigated in terms of the physicochemical properties of starches. The lightness values of the eight sweet potato starches were higher than 90, which was satisfactory for starch purity. The average molecular weight (M_W) and amylopectin average chain length (ACL) of sweet potato starches ranged from 6.93×10^7 g/mol to 16.57×10^7 g/mol and from 21.85% to 23.00%, respectively. Su16 starch with low amylose content and a large amount of short chains exhibited low crystallinity and thermal properties. These results suggested that the molecular structure of amylose and amylopectin was the main influencing factor in determining sweet potato starch physicochemical properties. The swelling power and water solubility of the starches ranged within 20.14–30.51 g/g and 5.28%–11.71% at 95 °C, respectively. Regarding pasting properties, all the starch samples presented high peak viscosity (>5500 cP) and peak temperature (>78 °C), indicating that sweet potato starch can be used as a thickener. All eight sweet potatoes varieties showed great application potential in the food industry.

1. Introduction

Sweet potato (*Ipomoea batatas* L.), which is a tuberous-rooted perennial plant that belongs to the family Convolvulaceae, is an economically important crop because of its high yield and wide adaptability [1]. It has rich nutritional value, high levels of carbohydrates, dietary fiber, and strong antioxidant activity [2]. Therefore, people consider sweet potato as diet and functional health foods to improve the dietary structure of humans [3]. Sweet potatoes are rich in certain antioxidants, such as polyphenolics, vitamin C and anthocyanins [4]. These phytochemicals have high free-radical scavenging activity, which exhibit antiviral, anticarcinogenic, anti-inflammatory, and vasodilatory properties [5]. Teow et al. [5] reported that antioxidant activities varied widely among the sweet potato varieties, and the purple color intensity of the sweet potatoes tended to be associated with high antioxidant activity. Purple and red-fleshed sweet potatoes can be used as novel sources of natural colorants. The increased interest in their antioxidant effects indicates that red and purple-fleshed sweet potatoes have potential use for the nutraceutical industry [6]. Therefore, selecting useful cultivars with high antioxidant activity is needed.

Starch plays important roles, such as food additive and stabilizer, in the development of food [7]. Starch can also be used in pharmaceutical industry as a carrier of substances, such as antioxidants and pharmaceutical active proteins [8]. Starches also have different properties and functionalities in different varieties of the same plant. Starch properties include granule size, swelling power and solubility, starch paste properties, pasting properties, and in vitro digestibility. Sweet potato starch, accounting for approximately 50%–80% of the root dry matter, is the main component of sweet potato root tuber. Some reports on sweet potato starch are currently available. Sajeev et al. [9] studied 3 white, 2 cream, and 2 orange sweet potato varieties and found that their textural, rheological, and gelatinization properties show significant differences among different varieties. Abegunde et al. [10] used 11 popular Chinese sweet potato varieties as experimental materials and found

Abbreviations: SEM, scanning electron microscopy; DNS, 3, 5-dinitrosalicylic acid.

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https://doi.org/10.1016/j.ijbiomac.2020.05.259
0141-8130/

that amylose content has a significant positive correlation with mean granule size, and swelling power and solubility of the starches show positive correlation with each other.

Sweet potatoes are perishable during storage, which results in waste of resources. Their abundant starch resources can be used with the extension of their industrial chain. Research on the specific purpose of sweet potato starch plays an important role in food industries, and the interest in finding new sources of starch with novel and unique properties is growing [11]. Structural and functional properties of starch determine its quality and applications, and the starch properties of different origins and varieties of the same crop are also different. Therefore, knowing the structural and functional properties of starch is critical to determine their potential uses. In this study, we selected eight Chinese sweet potatoes with the same planting conditions and growth environment to compare the morphological, structure, and functional properties of starches. This study on sweet potato starch would provide basis for its development and utilization.

2. Materials and methods

2.1. Materials

A total of eight varieties, including four light yellow varieties, Qin 5, Qin 9, 12-18-28, and Shang 19; two orange varieties, Su 16 and Qin 8; and two purple varieties, Qinzi 2 and Qinzi 3, were used in this study. These varieties were grown under similar planting conditions in an experimental field of Baoji Academy of Agricultural Sciences, Shaanxi, China and harvested in October 2018. The fresh tubers and flour of sweet potato were used as plant materials. Flour and flour extracts of sweet potato were prepared according to the method described by Wang et al. [12]. 1-Aminopyrene-3,6,8-trisulfonic acid (APTS) was purchased from Aladdin Reagent Co., Ltd. (Shanghai, China). All other reagents were of analytical grade.

2.2. Measurement of water, reduced sugar, anthocyanin, starch and amylose contents in tuber

The water content of fresh tuber was determined according to the air oven method. The reduced sugar content of fresh tuber was measured according to the DNS colorimetry method [13]. The anthocyanin content of fresh tuber was determined following the pH differential method [14]. Samples were diluted with two different solutions as follows: potassium chloride (0.025 M) at pH 1.0 and sodium acetate (0.4 M) at pH 4.5. Diluted samples were stored for 45 min in darkness, and the absorbances were measured at 530 nm and 700 nm with distilled water as a blank. The starch content of dry flour was measured using the anthrone-H_2SO_4 method described by Yang et al. [15]. The amylose content was determined through the iodine-binding method of Yong et al. [16]. The amylose content was evaluated from the absorbance of the starch iodine mixture at 620 nm. The standard curve was prepared with standard amylose and amylopectin samples.

2.3. Isolation of sweet potato starch

Sweet potato starch was isolated according to the alkaline steeping method of Abegunde et al. [10]. The root tubers were washed with water and cut into small strips. The strips were homogenized using a home blender. The homogenate was filtered with 100- and 200-mesh sieves successively and steeped in 0.1% NaOH aqueous solution for 12 h. The starch precipitate was washed thrice with 0.1% NaOH aqueous solution and thrice with distilled water. Finally, the precipitated starch was dried at 40 °C, ground into powder, and passed through a 100-mesh sieve.

2.4. Starch characterization

2.4.1. Color of sweet potato flour and starch

The colors of the starch and flour were measured using colorimeter (Colorimeter Ci7600, Aisaili Color Technology Inc., Shanghai) as L (lightness), $\pm a$ (redness/greenness), and $\pm b$ (yellowness/blueness) values. The total color difference (ΔE) was calculated follows: $\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2}$.

2.4.2. Morphology observation and granule size analysis of starch

The starch suspension in 50% glycerol was observed and photographed under a polarized light microscope (BX53, Olympus, Tokyo, Japan) under normal and polarized light [12]. The submicroscopic morphology of starch was observed using S-4800 SEM. The micrograph of each sample was taken at an accelerating voltage of 10 kV with 1000 × magnification. Starch granule size was measured by using a laser diffraction instrument (Mastersizer 2000, Malvern, England) [12]. Starch staining, sample preparation, and flow cytometry analysis followed the method by Yang et al. [17].

2.4.3. Molecular weight distribution of starch

The molecular weight distribution of starches was analyzed by using the GPC-RI-MALS (gel chromatography - differential - multi - Angle laser light scattering) method. The main analysis conditions were as follows: RI: Optilab T-rEX (Wyatt technology, CA, USA), and Pump: Series 1500 Pump, waters.

2.4.4. Amylopectin chain length distribution

The branch chain length distribution of amylopectin was analyzed using high-performance anion exchange chromatography (Dionex ICS- 5000, Thermo Scientific, Waltham, MA, USA) according to the method of Yang et al. [17]. The elution gradient was made with 1 M sodium acetate in 100 mM NaOH against 100 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 control was 0.4 mL/min.

2.4.5. X-ray diffraction (XRD) analysis and short-range ordered structure of starch

The crystalline structure of starch was analyzed with an X-ray diffractometer (D/Max2550VB+/PC, Rigaku Corporation, Tokyo, Japan). Samples were scanned over the range of 5°–50° with a step size of 0.02 [18]. The ordered structure of starch external region was detected with a Fourier transform infrared (FTIR) spectrometer (Nicolet iS50, Thermo Fisher Scientific, Massachusetts, America). The starch was scanned 32-fold with a 4 cm^{-1} resolution [19].

2.4.6. Light transmittance of starch

Light transmittance was determined following the method of Yang et al. [20] with some modifications. The 1% aqueous suspension of starches was heated in a water bath at 95 °C for 30 min. After cooling the slurry to room temperature, the light transmittance value of the supernatant was measured at 620 nm using a spectrophotometer (Blue Star B, Lab Tech Ltd., China).

2.4.7. Swelling power and solubility of starch

Swelling power and solubility of starch were determined through the method of Zhang et al. [21]. The starch sample (0.3 g) was mixed with 10 mL of distilled water and placed in a shaking water bath from 75 °C to 95 °C at 10 °C intervals for 30 min. The slurry was cooled and centrifuged at 3000 ×g for 20 min. The supernatant was decanted into aluminum cans and dried at 105 °C for 2 h. The dried supernatant and the sediment were weighed.

2.4.8. Thermal properties of starch

Starch thermal property was measured by differential scanning calorimetry (DSC; Q 2000, TA Instruments, Wood Dale, IL, USA). The sample (3 mg, db) was weighed into an aluminum pan, and water (9 μL) was added. The pan was hermetically sealed and allowed to stand (2 h, room temperature) before heating in the DSC. The sample pan was heated in 40 °C–130 °C at a rate of 10 °C/min. An empty pan was used as reference. Parameters recorded were gelatinization onset (To), peak (Tp), conclusion (Tc), temperatures, and enthalpy (ΔH, J/g).

2.4.9. Pasting properties of starch

Starch pasting property was analyzed by using Rapid Visco Analyzer (RVA 4500, Perten, Sweden). Then, 3 g of starch and 25 mL of deionized water were mixed in the RVA sample canister. The suspension was kept at 50 °C for 1 min, heated to 95 °C at a rate of 12 °C/min, and maintained at 90 °C for 2 min. Subsequently, the suspension was cooled down from 90 °C to 50 °C at a rate of 12 °C/min and held at 50 °C for 1 min. Parameters recorded were peak viscosity (PV), hot viscosity (HV), breakdown viscosity (BV), final viscosity (FV), setback viscosity (SV), and peak temperature (PT).

2.5. Statistical analysis

Data are presented as the mean standard deviation of triplicate measurements. Duncan test and one-way analysis of variance (ANOVA) were used for multiple comparisons with SPSS 23.0 Statistical Software Program. Probability (p) ≤ 0.05 indicates statistical significance. Hierarchical cluster analysis was employed using between-groups linkage as the cluster method and Euclidean distance as the interval measure.

3. Results and discussion

3.1. Chemical composition

Table 1 shows the water, reduced sugar, anthocyanin, starch, and amylose contents of sweet potato. The water content of sweet potato fresh tuber ranged from 68.03% to 76.70%, with the purple variety exhibiting the lowest water content. The result was similar to that (62.6%–73.6%) reported by Zhang et al. [21]. The reducing sugar content directly affected consumption and processing quality of sweet potato. The Shang 19 had the highest reduced sugar content. Sugar, which can be used as a substrate for dough fermentation, had tenderizing effects on bakery products such as bread and cake that positive effect their texture [7]. Only two purple sweet potatoes contained anthocyanins, and its contents ranged from 23.57 mg/100 g fw (Qinzi 2) to 27.34 mg/100 g fw (Qinzi 3). The different purple sweet potato varieties possessed different anthocyanin contents that depended on genotypes. Anthocyanin contents of red or purple fruits and vegetables ranged from 0.02 mg/g fw to 6 mg/g fw [5]. The anthocyanin contents of purple sweet potatoes are comparable to those of fruits and vegetables. Anthocyanin is a natural anti-aging nutritional supplement and the safest and most effective free radical scavenger identified [22]. Qinzi 2 and Qingzi 3 as sources of natural anthocyanins could have broad development prospect in the health care product industry.

The starch content of dry tuber ranged from 37.38% to 48.61%. Qinzi 3 had significantly higher starch content than other varieties. Our result was significantly higher than the result reported by Cartier et al. [23]. Starch content, which is controlled by genetic and environmental factors, is one of the important agronomic traits of sweet potato. In this experiment, the sweet potato varieties were cultivated in the same environmental conditions but varied greatly in starch content, indicating that the different starch content resulted from their different genotype backgrounds. Qinzi 3 and Shang 19 had high starch contents, which indicated that these two varieties were ideal starch sources. Amylose content varied significantly among the obtained starches with values ranging from 18.71% to 25.15%. Our result was similar to the amylose content (23.3% to 26.5%) of 11 representative genotypes of sweet potato with diverse geographic origins in China reported by Zhu et al. [24]. Lee and Lee [25] reported that amylose contents ranging from 16.5% to 18.5% in white, yellow, orange, and purple sweet potatoes. The different amylose content of different varieties appeared to stem primarily from the different genotype backgrounds. Su 16 showed the lowest amylose content, whereas Qin 8 showed highest amylose content. Amylose content plays an important role in the functional properties of starches, and the transparency and swelling of starch decrease with increasing amylose content [26].

3.2. Starch characterization

3.2.1. Hunter, L, a, and b, and other color parameters of sweet potato starch and flour

Hunter color values, L, a (+red/−green), and b (+yellow/−blue), of the eight sweet potato starches and flours are presented in Table 2. Color was an important criterion in evaluating starch quality. L values of starches from eight sweet potatoes ranged from 91.40 to 96.83. Baek et al. [27] showed that L values of sweet potato starches (82.85%–98.23%) were lower than that of wheat (100%) starches. Browning reaction pigments during grinding of sweet potatoes were considered as a main reason for the low L of sweet potato starch. The whiteness of our results was all over 90, which was satisfactory for starch purity. Shang 19 had high starch content and had the highest L among the eight sweet potatoes. Therefore, this variety may be more suitable for starch processing. The a and b values of starches from eight sweet potatoes ranged from −0.30 (Qin 5) to 0.36 (Qinzi 3) and from 2.99 (Qin 9) to 5.45 (Qinzi 3), respectively. All starches showed yellowish coloration, and the most obvious performance in Qinzi 3 was due to the anthocyanin effect. A co-pigmented substance between anthocyanin and protein may have caused these results [28]. L values of flours ranged from 62.28 (Qinzi 3) to 91.01 (Shang 19). a and b values were the highest in Qin 8, which may be due to Qin 8 having high carotene content. Orange and purple varieties were characterized by high $+a$ values, which was consistent with a study completed by Cartier et al. [23]. The high $+a$ and $+b$ values recorded in some of the sweet potato varieties, although advantageous in foods, may affect starch quality in the extraction and leaching of the pigments, resulting in discoloration of starch granules [29]. ΔE was highest in Shang 19.

3.2.2. Morphology and size distribution of starch

Starch granules were observed by SEM (Fig. 1). The eight starch granules of sweet potato were similar, exhibiting round, polygonal, oval, semi-oval, and hemispherical shapes with different sizes. The result was similar with the report of Chen et al. [30]. All starch granules exhibited the typical "Maltese cross," showing a dark cross at the center. Fig. 1 and Table 2 showed that the extracted starch granules had smooth surfaces with no cracks, suggesting purity, and L was above 90, indicating that our starch extraction method was suitable.

Granule size and size distribution are characteristics that markedly influence the functional properties of starch granules. Starch granule size was analyzed with a laser diffraction instrument (Fig. 1). Only three starches, including Shang 19, Su 16, and Qinzi 3, showed bimodal size distributions with small granule size of 1–4 μm and large granule size of 5–84 μm. Other starches showed unimodal size distributions with granule size of 4.5–84 μm. The volume distributions of eight starches were also significantly different. The mean diameters of starch granules were listed in Table 3 and ranged from 16.10 μm to 23.94 μm. The diameter was the lowest in Qin 9 and highest in Su 16. Lee and Lee [25] determined that purple root tuber had the smallest starch granules (D [3, 4] 18.8 μm). Guo et al. [31] found that the granule sizes of d (0.5), D [2, 3], and D [3, 4] of white, yellow, and purple sweet potatoes starch ranged within 11.70–17.24, 5.90–8.51, and 12.33–18.09 μm, respectively. Our result was slightly different from literature, which may be related to the differences in genotypes and growing conditions

Table 1
Water content, reduced sugar, anthocyanin, starch and amylose content of sweet potato.[a]

Varieties and lines	Flesh color	Water content (%)	Reduced sugar content (%)	Anthocyanin content (mg/100 g fw)	Starch content (%)	Amylose content (%)
Qin 5	Light yellow	69.70 ± 0.007d	1.24 ± 0.00d	–	42.25 ± 0.23c	23.09 ± 0.07bc
Qin 9	Light yellow	74.79 ± 0.012b	2.27 ± 0.04b	–	37.38 ± 0.59g	19.82 ± 0.25e
12-18-28	Light yellow	76.70 ± 0.002a	0.77 ± 0.01f	–	39.00 ± 0.35f	22.62 ± 0.41c
Shang 19	Light yellow	72.76 ± 0.002c	2.41 ± 0.19a	–	43.33 ± 0.51b	19.44 ± 0.01e
Su 16	Orange	72.50 ± 0.005c	1.32 ± 0.03d	–	41.72 ± 0.32cd	18.71 ± 040f
Qin 8	Orange	71.97 ± 0.003c	1.98 ± 0.02c	–	39.94 ± 0.74e	25.15 ± 0.40a
Qinzi 2	Purple	69.60 ± 0.002d	1.02 ± 0.01e	23.57 ± 0.66b	41.07 ± 0.52d	21.29 ± 0.06d
Qinzi 3	Purple	68.03 ± 0.006e	0.84 ± 0.06f	27.34 ± 0.72a	48.61 ± 0.33a	23.49 ± 0.36b

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

Table 2
Color values of sweet potato flours and starches.[a]

Varieties and lines	Sweet potato flours				Sweet potato starches			
	L	*a*	*b*	Δ*E*	*L*	*a*	*b*	Δ*E*
Qin 5	87.69 ± 0.08b	0.80 ± 0.03f	11.29 ± 0.03e	88.41 ± 0.09c	96.70 ± 0.01a	−0.30 ± 0.03f	3.02 ± 0.03f	96.75 ± 0.01a
Qin 9	87.81 ± 0.18b	1.01 ± 0.03e	12.82 ± 0.17c	88.74 ± 0.16b	96.08 ± 0.03b	−0.21 ± 0.04e	2.99 ± 0.03f	96.12 ± 0.03b
12-18-28	86.34 ± 0.10c	1.12 ± 0.02e	11.61 ± 0.10d	87.12 ± 0.09d	95.11 ± 0.16d	−0.12 ± 0.01d	4.01 ± 0.10c	95.19 ± 0.16d
Shang 19	91.01 ± 0.12a	0.23 ± 0.01g	7.64 ± 0.05f	91.33 ± 0.13a	96.83 ± 0.02a	−0.02 ± 0.02c	2.26 ± 0.13g	96.85 ± 0.01a
Su 16	84.48 ± 0.08d	7.07 ± 0.04d	17.47 ± 0.22b	86.56 ± 0.04e	94.76 ± 0.08e	−0.22 ± 0.01e	3.69 ± 0.03e	94.83 ± 0.08e
Qin 8	78.52 ± 0.11e	20.19 ± 0.08a	17.70 ± 0.01a	82.98 ± 0.08f	95.45 ± 0.08c	0.13 ± 0.03b	3.84 ± 0.10d	95.53 ± 0.09c
Qinzi 2	65.80 ± 0.08f	10.37 ± 0.05c	3.49 ± 0.05g	66.71 ± 0.09g	93.54 ± 0.08f	0.13 ± 0.01b	4.53 ± 0.11b	93.65 ± 0.08f
Qinzi 3	62.28 ± 0.11g	14.55 ± 0.17b	−3.89 ± 0.16h	64.08 ± 0.06h	91.40 ± 0.01g	0.36 ± 0.02a	5.45 ± 0.06a	91.56 ± 0.01g

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

[32]. Starch granule size plays an essential role that influences pasting parameters of starches. Starch with small starch granules, such as Qin 5 and Qin 9, can be used in cosmetic products and paper coating applications, which require relatively small starch granules.

Flow cytometry was used to classify starch granules. Flow cytometry is primarily used in the fields of medicine and microbiology [33]. It has gradually extended recently to the field of botany, which successfully used flow cytometry in protoplasts, nuclei, and chromosomes. This

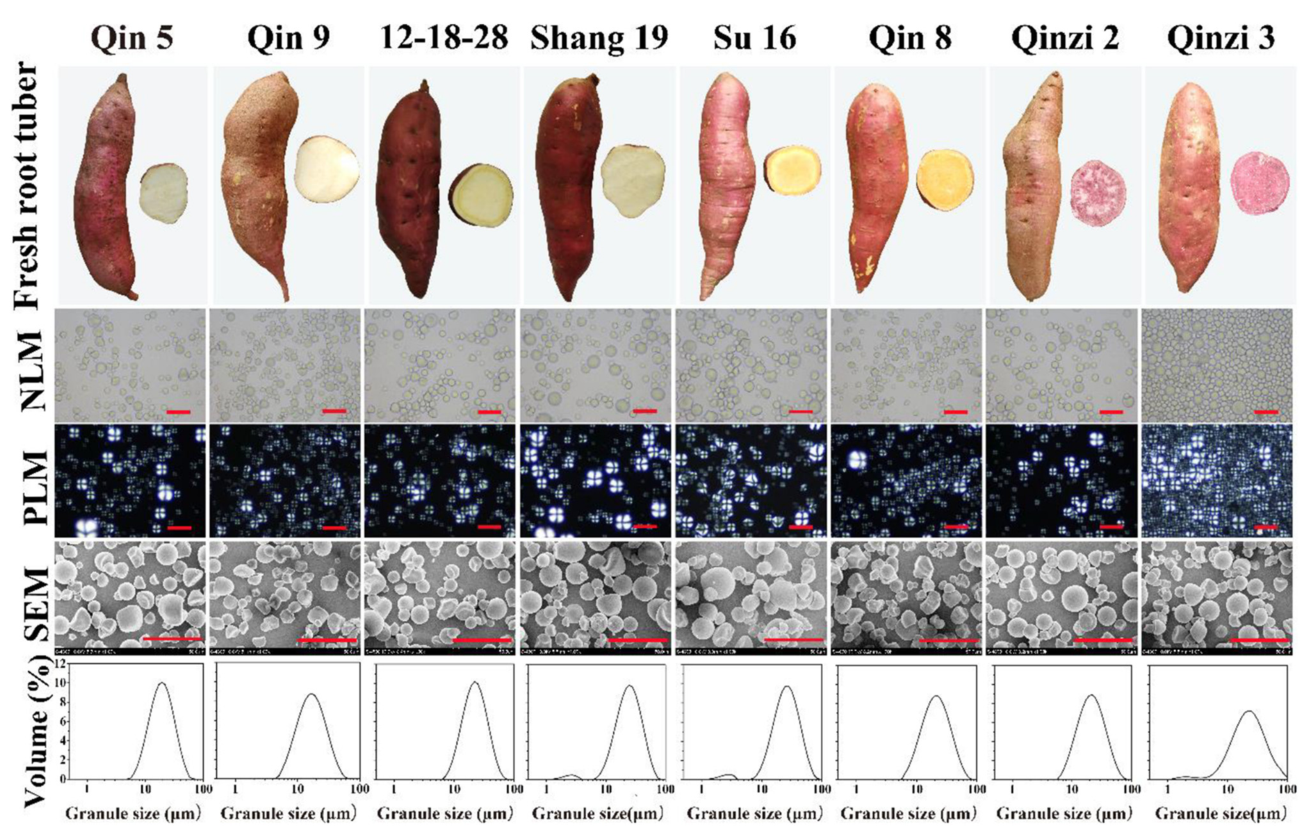

Fig. 1. The photos of sweet potato root tubers, the morphologies of starch granules under normal light microscope (NLM), polarized light microscope (PLM) and scanning electron microscope (SEM), and the granule size distribution of starches. Red scale bar = 50 μm.

Table 3
Granule sizes, average molecular weight (M_W), radius of gyration (R_Z), and molecular density (ρ) of starch.[a]

Varieties and lines	Granule size[b]			M_W ($\times10^7$ g/mol)	R_Z (nm)	ρ (g/mol/nm^3)
	d (0.5)	D [2, 3]	D [3, 4]			
Qin 5	17.90 ± 0.01g	16.08 ± 0.00f	19.66 ± 0.01h	14.30 ± 0.37b	245.36 ± 0.55b	9.66 ± 0.31e
Qin 9	16.10 ± 0.02h	14.41 ± 0.01h	23.62 ± 0.01g	12.49 ± 0.98e	221.00 ± 0.18f	11.54 ± 0.21c
12-18-28	21.06 ± 0.02d	19.25 ± 0.03a	27.29 ± 0.01b	8.59 ± 0.41g	165.08 ± 0.20g	19.11 ± 0.22b
Shang 19	22.61 ± 0.01b	17.11 ± 0.01e	24.53 ± 0.01f	14.18 ± 0.87c	236.17 ± 0.39d	10.74 ± 0.18d
Su 16	23.94 ± 0.00a	17.77 ± 0.02c	26.03 ± 0.02d	6.93 ± 0.42h	141.00 ± 0.36h	24.49 ± 0.46a
Qin 8	19.96 ± 0.02f	17.67 ± 0.01d	25.88 ± 0.03e	9.98 ± 0.45f	226.94 ± 0.48e	8.58 ± 0.40f
Qinzi 2	20.05 ± 0.01e	17.92 ± 0.01b	27.22 ± 0.02c	16.57 ± 0.66a	253.11 ± 0.10a	10.23 ± 0.48de
Qinzi 3	22.04 ± 0.01c	16.01 ± 0.01g	33.53 ± 0.00a	13.42 ± 0.90d	237.91 ± 0.68c	10.04 ± 0.18e

[a] Data are means ± standard deviation, n = 3. Values in the same column with different letters are significantly different ($p < 0.05$).
[b] Granule size is measured by laser diffraction instrument. 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.

method was rarely used in starch presently. We analyzed plots of forward-scattered light (FSC) against side-scattered light (SSC) and APTS against SSC and obtained a figure of unstained and APTS-stained starches to evaluate characteristics of the starch granules (Fig. 2). SSC, FSC, and APTS showed integral structure complexity, granule size, and fluorescence intensity, respectively. The eight starch granules of sweet potato were divided into three subgroups, P1, P2, and P3, but *p* values of the same subgroup were different among the eight starch granules. Qin 9 (P1 = 85.6%) contained larger and more complex granules. Starch granules of 12-18-28 and Qin 5 were basically similar in size and complexity. The smallest starch granules were found in Qinzi 3. P3 subgroup with the smallest and simplest granules contained fewer stained granules, which may have been due to the presence of few impurities in the starch. Results showed that flow cytometry can be used as a novel particle clustering method in crop starch.

3.2.3. Molecular weight distribution of starch

Table 3 shows the average molecular weight (Mw), radius of gyration (R_Z) and molecular density ($\rho = Mw / R_Z^3$) of sweet potato starches. The Mw of starch ranged from 6.93×10^7 to 16.57×10^7 g/mol. Kim et al. [28] found that the Mw of eight Korean sweet potatoes varied from 5.37×10^7 to 5.99×10^7 Da, which was lower than our results. The variety and experimental determination method may affect such differences among sweet potato. Yang et al. [17] reported that the M_W of sorghum starch, tartary buckwheat starch, common buckwheat starch, mungbean starch and pea starch were 19.5×10^7 g/mol, 9.0×10^7 g/mol, 10.7×10^7 g/mol, 10.6×10^7 g/mol, 7.7×10^7 g/mol, respectively. Zeng et al. [34] found that the M_W of waxy rice starch was 10.38×10^7 g/mol. The above results indicated that sweet potato starch had a high Mw compared to other crops, which may lead to its special starch physicochemical properties [35]. The R_Z and ρ of starches in the current study ranged from 141.00 (Su 16) to 253.11 nm (Qinzi 2) and 8.58 (Qin 8) to 24.49 g/mol/nm^3 (Su 16), respectively. The larger ratio of amylopectin long branched chains might result in higher R_Z. The maximum ρ indicated that the Su 16 starch had the most branches and was easily intertwined to enhance the viscoelasticity of the system.

3.2.4. Amylopectin chain length distribution

The branch chain length distributions of amylopectin (AP) are summarized in Table 4 and Fig. 3A. All of the sweet potato starches exhibited bimodal distribution. The main peaks of all starches were slightly different and appeared at DP 12–13. However, the second peaks of the eight starches all appeared at DP 46. Similar result to that obtained in the present study was observed in eight Korean sweet potatoes starches

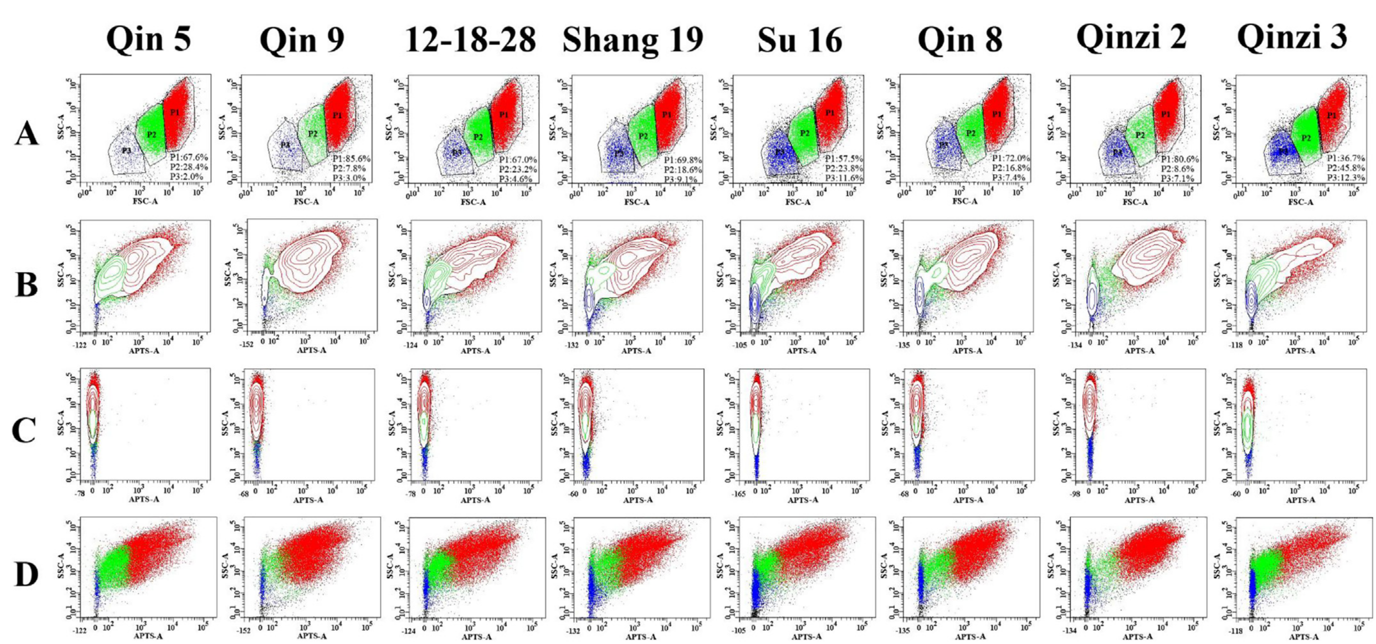

Fig. 2. Bivariate flow cytometric histograms of eight starches: (A) Forward scattered-side scattered (ASC-SSC) image; (B) fluorescence image; (C) imaging figure of unstained starch (negative control); and (D) imaging figure of 1-aminopyrene-3,6,8-trisulfonic acid (APTS) stained starch.

Table 4
Chain length distribution and average chain length (ACL) of amylopectin, relative crystallinity and IR ratio of starch.[a]

Varieties and lines	Chain length distribution (%)				Average chain length of amylopectin (%)	Relative crystallinity (%)	IR ratio	
	DP 6–12	DP 13–24	DP 25–36	DP ≥ 37			$1045/1022\ cm^{-1}$	$1022/995\ cm^{-1}$
Qin 5	22.30 ± 0.02e	47.23 ± 0.04b	14.89 ± 0.04b	15.58 ± 0.01b	22.59 ± 0.01bc	39.63 ± 0.08a	0.359 ± 0.010b	0.806 ± 0.006a
Qin 9	25.01 ± 0.06a	46.02 ± 0.40c	14.60 ± 0.20cd	14.37 ± 0.25c	21.85 ± 0.11f	36.37 ± 0.31d	0.343 ± 0.030b	0.652 ± 0.010d
12-18-28	22.96 ± 0.05c	46.24 ± 0.01c	14.76 ± 0.02bc	16.07 ± 0.04ab	22.65 ± 0.03b	32.86 ± 0.23f	0.312 ± 0.005c	0.673 ± 0.001c
Shang 19	21.26 ± 0.07f	46.90 ± 0.18b	15.53 ± 0.09a	16.33 ± 0.16a	23.00 ± 0.07a	39.56 ± 0.17a	0.402 ± 0.006a	0.625 ± 0.007e
Su 16	24.82 ± 0.09a	45.41 ± 0.24d	14.93 ± 0.15b	14.84 ± 0.19c	22.07 ± 0.09e	35.74 ± 0.06e	0.267 ± 0.003d	0.794 ± 0.010a
Qin 8	24.28 ± 0.03b	45.47 ± 0.04d	14.45 ± 0.04d	15.80 ± 0.04b	22.42 ± 0.02cd	37.15 ± 0.49c	0.346 ± 0.003b	0.757 ± 0.016b
Qinzi 2	22.42 ± 0.31de	48.48 ± 0.67a	14.45 ± 0.30d	14.68 ± 0.68c	22.20 ± 0.32de	38.25 ± 0.41b	0.317 ± 0.003c	0.626 ± 0.003e
Qinzi 3	22.55 ± 0.02d	48.21 ± 0.05a	14.72 ± 0.07bc	14.51 ± 0.01c	22.18 ± 0.02e	38.12 ± 0.08b	0.307 ± 0.002c	0.751 ± 0.021b

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

[28]. The branch chains of AP were usually classified into the following types according to degree of polymerization (DP): A chain (DP 6–12), B1 chain (DP 13–24), B2 chain (DP 25–36), and B3+ chains (DP ≥ 37). Table 4 showed that the AP of eight sweet potato had a large number of shorter A chain and the highest proportion of B1chains. The average chain length (ACL) of sweet potato starches was significantly different among eight varieties, and varied from 21.85% (Qin 9) to 23.00% (Shang 19). Yang et al. [17] reported that the ACL of the five coarse grains ranged from 21.2% to 23.5%, which reflected that the ACL of sweet potato was close to that of coarse grains. Compared with other starch, the content of the short A chains in the starch of Shang 19 was the lowest, while the contents of B3 chains and ACL were the highest. Genotypes may be responsible for the different distribution of eight sweet potatoes branch chain length. Some scholars have suggested that pasting properties were also affected by the AP chain length distribution. The lower the proportion of A chains, the lower the PV [36]. Li et al. [37] found starches with a higher proportion of long AP chains (DP ≥ 37) were characterized by a greater degree of swelling power. Therefore, it could be speculated that AP chain length distribution greatly affected the physicochemical properties of starch.

3.2.5. Crystalline structure of starch

The crystalline structure of starch granule was determined by XRD and the pattern is shown in Fig. 3B. Six of eight starches showed 2θ peaks at approximately 5.6°, 15°, 17°, 18°, and 23°, whereas the remaining starch showed strong diffraction peaks at approximately 15° and 23° 2θ with an unresolved doublet at approximately 17° and 18° 2θ. The starches of eight sweet potato varieties presented two types through XRD patterns, namely, C and A patterns, as follows: C_A type for Qin 8, Qin 9, Qingzi 2, 12-18-28, Qingzi 3, and Su 16; and A type for Shang 19 and Qin 5. The eight Korean sweet potato varieties reportedly contain A- and C_B-type starches [28], whereas the orange, white, and purple sweet potatoes contain C_A-type starch [25]. The above results indicated that the crystalline types of sweet potato starch can be related to the cultivation region, growth condition, variety, and genotype [16]. Table 4 shows that the relative crystallinities of sweet potato starches

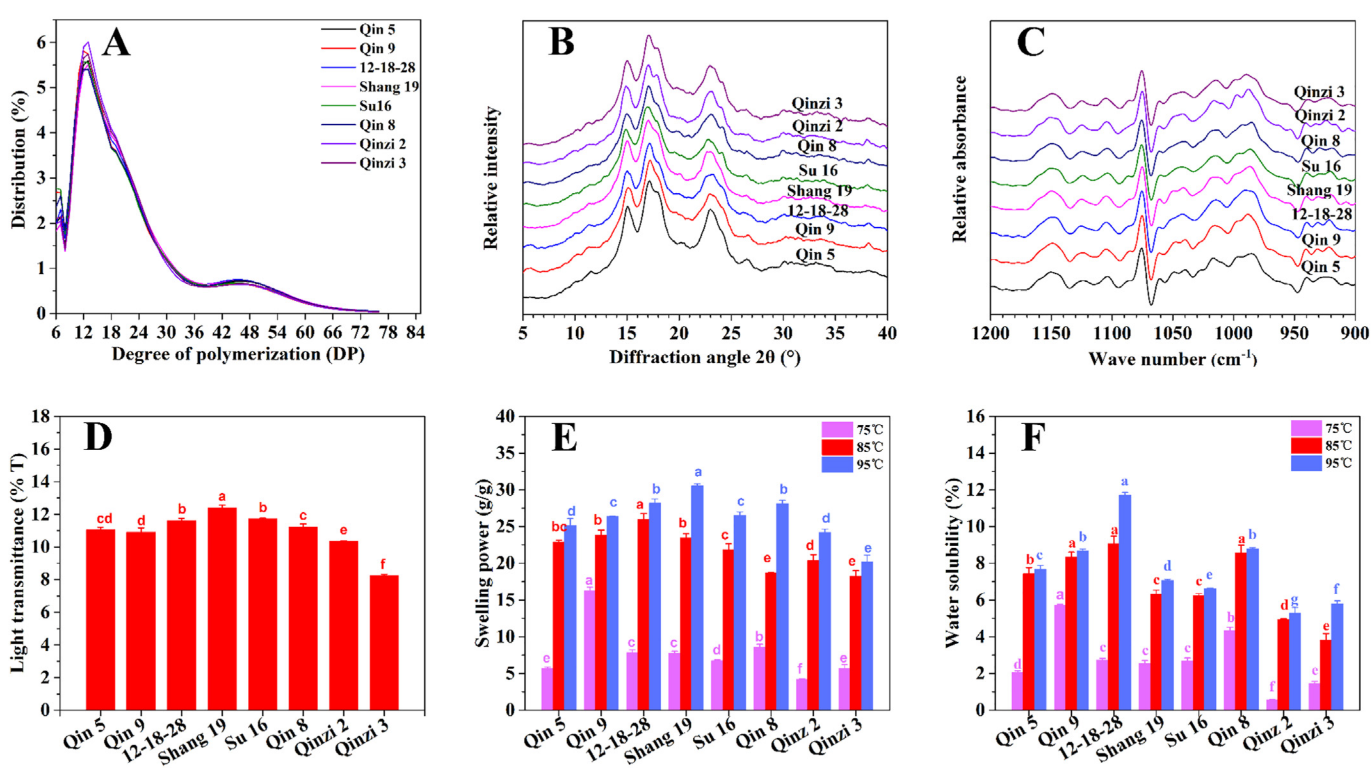

Fig. 3. (A) Amylopectin chain length distribution; (B) X-ray diffraction patterns of starch; (C) ordered structure (FTIR) of starch; (D) light transmittance of starch; (E) swelling power of starch; (F) water solubility of starch;

ranged from 32.86% to 39.56%. The crystallinity of Qin 5 and Shang 19 reached 39.63% and 39.56%, respectively, which were higher than those of other varieties. Our result was significantly higher than the results reported by Guo et al. [31]. The chemical structure, especially composition of starches, may affect such differences among starches. The crystallinity showed a significantly negative correlation with short chain content, but an obviously positive correlation with AP long chain content [37]. Longer chains could form more perfect crystalline structures. Qin 5 and Shang 19 starches contained higher proportions of medium and long chains (Table 4), and higher crystallinity than the other starches, which was consistent with the previous studies [37].

3.2.6. Ordered structure

The FTIR spectra, 1045/1022 cm^{-1} ratio, and 1022/995 cm^{-1} ratio of the starches are shown in Fig. 3C and Table 4. No difference was observed in the detected peaks of the eight sweet potato varieties, indicating that no difference existed in the chemical groups among the sweet potato varieties. The spectral characteristics are three typical absorption peaks with maximum absorbances at 995, 1022, and 1045 cm^{-1}. Peak intensity ratios at 1045/1022 and 1022/995 cm^{-1} are used to reflect the ordered degree and the proportion of amorphous to ordered carbohydrate structure, respectively [13]. Jiang et al. [38] found positive correlation between ordered degree and crystallinity of starch. In the present study, the 1045/1022 cm^{-1} ratio of the eight sweet potato starches ranged 0.267–0.402 and was the highest in Qin 5. This finding was consistent with the results of high crystallinity of Qin 5 in the XRD. The 1022/995 cm^{-1} ranged from 0.625 to 0.806, which was lower than report previously by Guo et al. [31]. The starch of Shang 19 had significantly different ratios of 1045/1022 and 1022/995 cm^{-1} from the other starches, indicating that the starch of Shang 19 had different short-range ordered structure. Swelling power, pasting viscosity, and hydrolysis of starch are significantly influenced by the ordered structure in starch external region [39].

3.2.7. Light transmittance of starch

Light transmittance describes the degree of transparency of starch paste, as the most external characteristic of starch paste that affects appearance and acceptability of starch products. The light transmittances of the eight sweet potato starches are presented Fig. 3D. The light transmittance ranged from 8.22% to 12.40%. Qinzi 3 had the lowest light transmittance, and Shang 19 had the highest light transmittance. Light transmittance is influenced by granule size and amylose content; an increase in amylose content reduces transparency of starch paste [40]. In the present study, Shang 19 and Su 16 had low amylose and big granule size, thereby exhibiting high light transmittance. Light transmittance of Shang 19 was higher than Su 16, which may have been because of the starch extraction process, whereas Su 16 tubers contained a number of pigments, resulting in poor starch color and low transparency. The light transmittance of potato starch was higher than that of sweet potato starch, because potato starch contained larger granules and distant bonds between molecules [32]. High light transmittance starch is often used as a thickener for confectionery or edible films.

3.2.8. Swelling power and solubility of starch

Fig. 3E and F shows swelling power and solubility of the starch from eight sweet potatoes at different temperatures. The swelling and solubility showed similar changing patterns as temperature increased. Swelling power of starches at 75 °C ranged from 4.20 g/g to 16.24 g/g. As 85 °C was reached, its swelling power average increased by approximately 14 g/g. Temperature elevation from 85 °C to 95 °C led to small increment in its swelling power, compared with the value obtained at 75 °C. The swelling power is similar with previous reports [41]. Swelling power of starches at 95 °C ranged from 20.14 to 30.51 g/g, with the highest value found in Shang 19.The extent of interaction between the starch chains results in changes in the swelling power and solubility of the starch [21]. The extent of this interaction was influenced by amylose content, branching degree and branch-chain length of amylopectin, crystalline structure. Starches with a higher proportion of long AP chains (DP ≥ 37) are characterized by a greater degree of swelling power. Amylose restrains swelling and maintains the integrity of swollen granules. For Shang 19, low amylose content and a large amount of long chains were the main factors causing higher swelling power. Differences in amylose content and AP molecular structure among eight sweet potato varieties may be the reason for the different swelling power.

The solubility has a smaller change compared with the swelling power but also has a large change at 85 °C. The water solubility of starches at 85 °C and 95 °C ranged from 3.82% (Qingzi 3) to 9.06% (12-18-28) and 5.28% (Qingzi 2) to 11.71% (12-18-28), respectively. At 85 °C, the water solubility (53.4%–85.8%) of starches from purple/white-fleshed sweet potatoes had higher values than our results [24]. Guo et al. [31] reported that solubility at 95 °C ranged from 11.7% to 16.6% among the nine sweet potato starches. In the present study, starch of purple sweet potato varieties showed the lowest solubility. The above results proved that the growth environment, genotype, variety, and assay method may be factors affecting solubility.

3.2.9. Thermal properties of starch

The thermograms and thermal parameters of starch are shown in Table 5. Some variations in the gelatinization temperatures were observed among the eight sweet potatoes. To of starch had a range of 65.91 °C–73.94 °C. The result was higher as compared with Yong et al. [16]. Tp for all starches were similar to those found by Zhu et al. [24] within 75.21 °C–79.35 °C. The range of gelatinization temperature and the gelatinization temperatures are related to the arrangement of starch components in the granule and granule size distribution. Qingzi 2 had higher Tp and Tc than other varieties, which was related to the higher proportion of chains with B1 (Table 4). B1 chains favour the dense packing of amylopectin chains in crystalline regions making these structures thermally stable. The gelatinization temperature (Tc–To) range was the highest in 12-18-28 (16.44 °C). This result may reflect the great degree of heterogeneity in the starch crystallites within granules. ΔH is related to the crystal loss and the arrangement of the double helix structure of amylopectin [29]. The eight starches ranged from 2.96 J/g to 11.51 J/g for ΔH, indicating that a significant difference exists in the internal granule structure of amylopectin between varieties. ΔH of sweet potato starches is positively correlated with their relative crystallinities [16]. In the present study, Qin 5 and Shang 19 had a high ΔH, which agreed with the high crystallinity of XRD analysis. The thermal properties of starch are affected by granule size, amylose content, crystalline structure, and granule ultrastructure [42]. A larger amount of extremely short chains in amylopectin reduced the efficiency of packing in the starch crystallinity and caused a decrease in the stability of the double helix, resulting in lower gelatinization temperature and enthalpy [39]. Su 16 had low amylose content (Table 1), large granule size and larger amount of extremely short chains; thus, Su 16 harboured the lowest thermal properties (Table 5) representing a unique starch for some applications.

3.2.10. Pasting properties of starch

The essence of starch pasting properties is that water molecules destroy the association between starch particles, leading to the break of hydrogen bonds between ordered (crystal) and disordered (amorphous) starch molecules, which form hydrophilic colloidal solution. The pasting properties of eight sweet potato starches are presented in Table 5. The PV of the starch ranged from 5578 cP to 6475 cP, being lowest for Qing 5 and highest for Su 16 with an average value of 5910 cP. The PVs of sweet potato starches were measured and showed high viscosity. These data above were in accordance with that reported in previous study [12]. The high HV starch would be preferred in applications that require high starch consistency during prolonged cooking. Qingzi 3 had the highest HV and lowest BV. BV is an estimation of the resistance of the paste to disintegration in response to heat and

Table 5
Thermal properties and pasting properties of starch.[a]

Varieties and lines	Thermal parameters[b]				Pasting parameters[c]					
	To (°C)	Tp (°C)	Tc (°C)	ΔH (J/g)	PV (cP)	HV (cP)	BV (cP)	FV (cP)	SV (cP)	PT (°C)
Qin 5	73.94 ± 0.30a	78.63 ± 0.06b	85.08 ± 0.36b	11.51 ± 0.11f	5578 ± 29d	2282 ± 15g	3296 ± 17c	3243 ± 18f	961 ± 3b	82.0 ± 0.4a
Qin 9	71.25 ± 0.09c	76.71 ± 0.04d	83.66 ± 0.32c	5.22 ± 0.01c	5880 ± 31b	2723 ± 24d	3157 ± 7d	3370 ± 7d	647 ± 8g	75.0 ± 0.1g
12-18-28	68.78 ± 0.32e	77.86 ± 0.34c	85.22 ± 0.51ab	5.31 ± 0.07c	5909 ± 38b	2560 ± 32f	3349 ± 27b	3316 ± 23e	757 ± 13d	78.6 ± 0.5e
Shang 19	72.14 ± 0.26b	77.31 ± 0.36c	84.72 ± 0.34b	10.42 ± 0.16e	5580 ± 32d	2269 ± 20g	3313 ± 23c	2944 ± 12g	681 ± 7f	80.8 ± 0.1bc
Su 16	65.91 ± 0.21f	75.21 ± 0.57e	82.14 ± 0.44d	2.96 ± 0.04a	6475 ± 50a	2672 ± 39e	3803 ± 4a	3450 ± 18c	778 ± 10c	76.5 ± 0.5f
Qin 8	70.23 ± 0.43d	77.32 ± 0.35c	84.80 ± 0.28b	3.14 ± 0.00b	5810 ± 37c	2844 ± 21b	2966 ± 15e	3526 ± 33b	688 ± 5f	79.6 ± 0.5d
Qinzi 2	73.84 ± 0.05a	79.35 ± 0.05a	85.71 ± 0.07a	8.06 ± 0.08d	5585 ± 34d	2782 ± 1c	2812 ± 3f	3507 ± 17b	725 ± 7e	81.1 ± 0.4b
Qinzi 3	71.33 ± 0.29c	77.72 ± 0.12c	83.79 ± 0.28c	5.34 ± 0.02c	6462 ± 48a	3829 ± 28a	2634 ± 22g	5003 ± 14a	1174 ± 12a	80.2 ± 0.5cd

[a] Data are means ± standard deviation, n = 3. Values in the same column with different letters are significantly different ($p < 0.05$).
[b] To, gelatinization onset temperature; Tp, gelatinization peak temperature; Tc, gelatinization conclusion temperature; ΔH, gelatinization enthalpy.
[c] PV, peak viscosity; HV, hot viscosity; BV, breakdown viscosity (PV-HV); FV, final viscosity; SV, setback viscosity (FV-HV); PT, peak temperature.

shear [10]. Thus, Qingzi 3 had higher resistance to heat and shear than the other starches. Regarding FV, Shang 19 had the lowest and Qinzi 3 had the highest. Meanwhile, SV ranged from 647 cP to 1174 cP; Qin 9 had the lowest SV and Qinzi 3 had the highest SV. The SV shows the tendency of starch paste to retrograde; the higher SV indicates a lower stability of starch cold viscosity [43]. Thus, Qinzi 3 with high FV and SV presents poor stability and tendency to retrograde. The PT ranged from 75.0 °C to 82.0 °C and was highest in Qin 5. This result agreed with the high crystallinity of Qin 5. Abegunde et al. [10] reported that the PT of sweet potato starch popularly used in Chinese starch industry ranged from 67.20 to 73.20 °C, which was lower than our result. Differences in PT of starches may be related to environmental factors and genotype. Starches with high PV and BV such as 12–18-28 and Su 16 can be considered for use as thickening or gelling agents. However, low PV starches such as Qin 5 and Qinzi 2 were suitable to produce weaning food ingredients. The pasting properties of starches are influenced by granule morphology, size, amylose content, crystalline structure, and swelling power [44].

3.3. Cluster analysis of starch

In order to compare the relationships of different sweet potato varieties, the hierarchical cluster was performed based on the structural and functional properties of starches (Fig. 4). The dendrogram analysis based on average linkage showed that the eight sweet potato varieties consisted two major clusters. Qingzi 3 starch was separated from the other seven starches at a linkage distance of 25. As for the remained seven varieties, there were two groups at the distance of approximate 6. One group contained Su 16. The another group had sweet potato variety, Qin 5, Qin 9, 12-18-28, Shang 19, Qin 8, Qinzi 2. The Qin 5 and Shang 19 could be further separated from Qin 9, 12-18-28, Qing 8, Qinzi 2 at the distance of 3. Shang19 and Qin5 showed A type and high crystallinity, high proportion of long chains and similar viscosity and thermal characteristics, which was consistent with the result of cluster analysis. Cluster analysis result indicated that the characteristics of sweet potato starch with same color was also different, which was mainly determined by the genotype background.

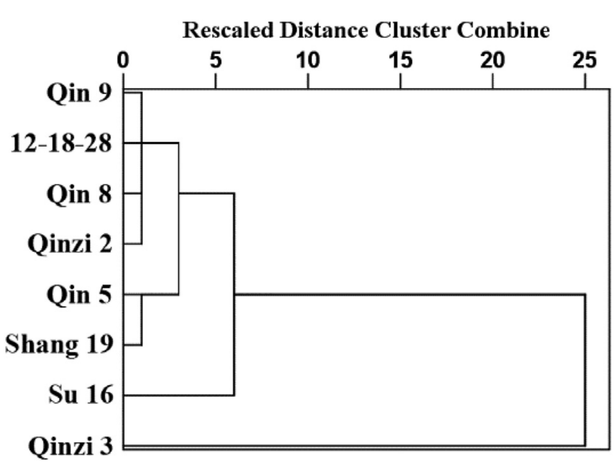

Fig. 4. Dendrogram generated by hierarchical cluster analysis based on structural and functional property parameters of starches.

4. Conclusion

In this study, the extracted starch granules were smooth with no cracks, and *L* was above 90, indicating that natural starch with satisfactory purity can be obtained under laboratory conditions. Starch granules of the eight sweet potatoes were round, polygonal, oval, and semi-oval shapes with granule sizes ranging from 16.10 μm to 23.94 μm and exhibited A and C_A-type XRD pattern. Different chain length distribution, particularly larger amount of short AP chains, reduced the efficiency of packing in the starch crystallinity and caused a decrease in the stability of the double helix, which led to lower gelatinization temperature and enthalpy, whereas a higher proportion of long AP chains and ACL were easy to form a stable double helix structure and high crystallinity. These results provided guidance for understanding of the characteristics of AP on sweet potato starch. The Shang 19 can be used for food application such as confectionery or edible films by light transmittance, while Qin 5 and Qin 9 with small starch granules can be used in cosmetic products and paper coating applications. These information added potential values and application prospects for the industrial dedicated applications of sweet potato.

Declaration of competing interest

There are no conflicts of interest regarding this paper.

Acknowledgement

This work was supported by the National Key Research and Development Program of China (2019YFD1000702), Special Project for the Construction of Modern Agricultural Industry Technology System (CARS-11-C-25), Shaanxi Provincial Modern Crops Seed Industry Project (20171010000004), Shaanxi Province Key Research and Development Projects (S2018-YF-TSLNY-0005) and Minor Grain Crops Research and Development System of Shaanxi Province (2009–2018).

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