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Research article

Study on physicochemical, structural, and functional properties of Zhengdan958 and Xianyu335 cornstarch from newly harvested corn under postharvest ripening conditions at ambient temperature

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ABSTRACT

The importance of starch in nutrition and industry is unquestionable. This study investigated the changes in physicochemical, structural, and functional properties of cornstarch from newly harvested Zhengdan958 (Zd958) and Xianyu335 (Xy335) corn during for 0, 20, 40, and 60 d at ambient temperature. The results showed no significant changes in the proximate components and apparent structure of Zd958 and Xy335 cornstarch under postharvest ripening conditions. Compared with 0 d, the molecular weight distribution and mass fraction of Zd958 and Xy335 cornstarch have changed significantly, the relative crystallinity (RC) has significantly increased from 26.4% to 26.5%–28.8% and 28.4%, and R1045/1022 has significantly increased from 0.828 to 0.826 to 0.843 and 0.883, respectively. The changes in structure indicated that the synthesis and rearrangement of cornstarch molecules formed highly ordered crystalline structures, and the ordered structures of long-range and short-range molecules increased. Moreover, the changes in structure affected the pasting characteristics and texture profiles of cornstarch, therefore, affecting the final food quality.

1. Introduction

China's corn planting area and yield rank the top two in the world. The planting area and yield of corn in Northeast China account for 37.3% and 40.2% of the country, respectively [1], and the quality and yield of corn in Northeast China play an irreplaceable role in ensuring national food security [2]. Newly harvested corn is usually mature in shape but not fully mature in physiology at harvest time, it is usually stored for a short or long time at ambient temperature during postharvest ripening until eating or processing. It was reported that biochemical and nutritional changes have occurred in cereals and legume grains under postharvest ripening conditions

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[3,4]. And the relationship between these changes and the physical and chemical composition has become increasingly important [5]. Furthermore, long-term storage would lead to the hardness increase of grains and postharvest deterioration, as well as the change of carbohydrate content, especially the starch changes had a great impact on the edible quality and processing properties [6].

It is well known that starch is the key ingredient of starch-based food and has a great impact on food properties and consumer acceptance [7]. Cornstarch is the main component of corn kernels, accounting for 78% of mature corn kernels [8]. Many reports have confirmed that changes in the physicochemical and structural properties of starch affected its functional properties [9,10]. It was found that the starch content of different types of corn significantly increased during storage, the average chain length distribution of amylopectin increased, resulting in changes in starch gelatinization characteristics, and the peak viscosity was increased from 128.9 to 161.7 (RVU) to 162.6–171.2 (RVU) [6]. Another study has shown that temperature has a significant impact on the physicochemical and gelatinization characteristics of corn during storage, and the change of gelatinization characteristics is the result of the interaction between disulfide bond and starch [11]. Although large numbers of studies have been carried out on the functional properties of cornstarch [12,13], few studies have been conducted on the physicochemical, structural, and functional properties of cornstarch during postharvest ripening storage. Therefore, managers must understand the changes in physicochemical, structural, and functional properties of cornstarch from newly harvested corn during the postharvest ripening process to maintain or improve corn kernel quality.

Our team has been engaged in the research on nutrition and quality of corn after harvest in Northeast China, including short-term and long-term storage and grain processing of corn [14,15]. Considering the great importance of corn preservation to the food industry, the study aims to investigate and compare the changes in the proximate components, molecular weight distribution, crystal structures of cornstarch isolated from newly harvested Zd958 and Xy335 corn during storage for 60 d, as well as the effects of these changes on the pasting properties and texture profile of cornstarch. This study is very important to provide information for the industrial application of cornstarch in improving the processing performance of starchy foods and provide a reference for determining the best time for corn deep processing.

2. Materials and methods

2.1. Samples and reagents

Newly harvested corn (Zd958 and Xy335) was collected from Jinzhou (Jilin, China, 43°03′N; 125°17′E) and stored at ambient temperature for 60 d. All corn samples used for preservation were free of pests and chemicals and were tested on days 0, 20, 40, and 60 d. The Amylose/Amylopectin assay kit and D-glucose (GOPOD-FORMAT) assay kit were purchased from Megazyme International Co., Ltd. (Ireland). LiBr was purchased from Sigma Chemical Co., Ltd. (St. Louis, MO, USA). Dimethyl sulfoxide (DMSO, HPLC Grade) was purchased from Fisher Scientific, Co., Ltd. (USA). All other chemicals purchased from Beijing Chemical Works (Beijing, China) were analytical grade.

2.2. Extraction of cornstarch

Cornstarch extraction was carried out according to Ref. [6] with some modifications. Corn kernels were soaked in 0.2% sodium bisulfite solution at 15 °C for 48 h to inactivate the enzymes, removed episperm and embryo with tweezers, and then ground with water at a ratio of 1:2 (w/v) using a blender (JYL-Y20, Joyoung Co., Ltd., Shandong, China). The slurry was filtered through the 100-mesh and 200-mesh sieves, respectively, then the filtrate was combined into a centrifuge tube and left at room temperature for 4 h. The starch precipitation was centrifuged at 2, 000 g for 10 min (Z36HK, Hermle Labortechnik GmbH Co., Ltd, Germany), washed with distilled water several times, and removed the yellow part of the upper layer, repeated the above process five times until the pH of the starch filtrate was 7. The cornstarch was dried in a 40 °C blast drying oven (101A-BT, Shanghai Experimental Instrument Co., Ltd, Shanghai, China) for 24 h, then ground with a mortar, and stored in a glass dryer for further study.

2.3. Proximate components

The content of moisture, ash, and protein was determined according to the Chinese national standard GB 5009-2010. The content of fat was determined according to the Chinese national standard GB 5009-2003 [16]. The content of amylose was determined by Amylose/Amylopectin assay kit according to the instructions.

2.4. Scanning electron microscope (SEM)

The apparent structure of cornstarch was observed according to the method described by Wang et al. [17] with slight modifications. The cornstarch was spread evenly on the conductive adhesive tapes, pasted on the loading platform, and sputter-coated with gold (JS-1600 M, Beijing HTCY Technology Co., Ltd., Beijing, China) for 60 s, then observed using an SEM (TM3030plus, Hitachi Tech Desktop Microscope, Japan) at a voltage of 5 kV with a magnification of 4000 and 8000× to obtain the apparent structure micrographs.

2.5. Molecular weight distribution

The average molecular weight (Mw) of cornstarch was analyzed by the combination of high-performance size exclusion

chromatography, multi-angle light scattering, and refractive index detection (HPSEC-MALS-RI) according to Teng et al., Lin et al., Martinez et al., and Roman et al. [18–21] with some modifications. First, 40 mg cornstarch and 2 mL DMSO were put into a 15 mL threaded centrifuge tube, then placed centrifuge tube in a boiling water bath, and shaken until the cornstarch is completely dissolved. After that, added 6 mL 95% ethanol solution into the centrifuge tube, centrifuged at 4, 000 g for 5 min, and removed the supernatant. Finally, added 5 mL mobile phase to the centrifuge tube, placed in the boiling water bath for 1 h to ensure that the gel group is completely dissolved, then filtered through a 1 μm organic membrane. The filtrate was injected into the HPSEC-MALS-RI system consisting of a pump (Agilent 1100, Agilent Technologies, Waldbronn, Germany), a quantitative ring with 200 μL injection volume and three serially connected gel columns (OHpak SB-804 HQ, OHpak SB-805 HQ, and OHpak SB-806 HQ, Shodex Showa Denko K.K., Tokyo Japan). The mobile phase was 90% dimethyl sulfoxide (DMSO) and 50 mmol/L lithium bromide (LiBr) solution, and the flow rate was 0.6 mL/min. ASTRA5.3 software (Wyatt Technology) was used for data processing.

2.6. X-ray diffraction (XRD)

The crystal structures of cornstarch were observed using an X-ray diffractometer (D/Max 2500 PC Rigaku, Japan) according to the method described by Wang et al. [17] with slight modifications. The diffractometer was operated at a generator voltage of 40 kV and an incident current of 40 mA with a scanning diffraction angle of 5–40°/s (2θ) at a step size of 0.02°/s. MDI jade5.0 software (Materials Data, Inc., California, USA) was used for data processing, and the RC was calculated as the ratio of the crystallized area to the total diffraction area.

2.7. Fourier transform infrared spectroscopy (FT-IR)

Cornstarch and KBr were thoroughly mixed at a ratio of 1:250 (w/w), ground, and pressed into tablets. The tablets were then determined using a spectrometer (Vertex70, Bruker, Germany) at a scanning wave range of 400–4000 cm^{-1} with 32 scans and a resolution of 4 cm^{-1} according to the method described by Wang et al. [17]. The obtained spectra were deducted from background and deconvoluted after baseline calibration using OPUS5.0 software, The deconvolution range is 1200–800 cm^{-1}, the half peak width is 19 cm^{-1}, and the enhancement factor is 1.9 [22]. Then calculated the relative absorbance ratios at 1045 cm^{-1} and 1022 cm^{-1}.

2.8. Pasting characteristics

Cornstarch pasting was determined by a rapid viscosity analyzer (RVA-TecMaster, Perten, Australia) according to the method described by Wang et al. [17] with slight modifications. Put 2.50000 ± 0.0005 g cornstarch and 25.0000 ± 0.0010 g deionized water into the special aluminum box in RAV, stirred evenly, and left at room temperature for 10 min. Cornstarch pasting was measured under the following conditions of the speed of 160 rpm at 50 °C (held for 1 min), then increased to 95 °C at a rate of 15 °C/min (held for 3 min), and finally decreased to 50 °C at a rate of 15 °C/min (held for 2 min). The pasting temperature (PT), peak viscosity (PV), breakdown viscosity (BV), and final viscosity (FV) values were obtained from pasting graphs.

2.9. Texture characteristics

The starch paste after RVA determination was placed in the refrigerator at 4 °C for 12 h to get the starch gel. Gel texture characteristics of cornstarch (including hardness, adhesiveness, gumminess, and springiness) were determined with a texture analyzer (TA. XTplus, Stable Micro Systems Co., Ltd., Britain) according to Zhao et al. [23] with some modifications. TA/BE back extrusion device with a P/36R probe was selected and cornstarch gel was placed on the fixed position of the platform. The test parameters were set as follows: the induction force was 5 g, the initial speed was 1.0 mm/s, the test speed was 2.0 mm/s, the compression ratio was 60%, and the time interval between two compressions was 5 s. Each sample was tested 10 times. The computer of the texture analyzer was used to control the instrument, record, and analyze the data.

Table 1
Analysis of proximate components of cornstarch (g/100 g).

Varieties	Time (d)	Moisture	Ash	Protein	Fat	Apparent amylose
Zd958	0	8.01 ± 0.64[a]	0.21 ± 0.07[a]	0.24 ± 0.06[a]	0.24 ± 0.03[a]	23.04 ± 0.36[a]
	20	8.26 ± 0.07[a]	0.20 ± 0.05[a]	0.21 ± 0.07[a]	0.28 ± 0.08[a]	24.21 ± 0.27[a]
	40	8.23 ± 0.25[a]	0.24 ± 0.04[a]	0.26 ± 0.03[a]	0.21 ± 0.05[a]	23.96 ± 0.43[a]
	60	8.30 ± 0.06[a]	0.14 ± 0.02[a]	0.23 ± 0.07[a]	0.20 ± 0.02[a]	23.83 ± 0.37[a]
Xy335	0	8.55 ± 0.35[a]	0.19 ± 0.01[a]	0.19 ± 0.01[a]	0.25 ± 0.06[a]	23.19 ± 0.31[a]
	20	8.33 ± 0.07[a]	0.21 ± 0.02[a]	0.25 ± 0.09[a]	0.18 ± 0.05[a]	24.45 ± 0.49[a]
	40	7.82 ± 0.15[a]	0.19 ± 0.01[a]	0.19 ± 0.09[a]	0.19 ± 0.03[a]	22.49 ± 0.59[a]
	60	7.53 ± 0.08[a]	0.20 ± 0.01[a]	0.20 ± 0.08[a]	0.20 ± 0.03[a]	22.70 ± 0.38[a]

Different letters are significantly different between each column by $p < 0.05$. Values are the mean ± standard deviation of three independent replicates ($n = 3$).

2.10. Statistical analysis

Origin 8 (OriginLab Corporation, USA) was used to draw curves. SPSS 22 software (SPSS Inc., Chicago, IL, USA) was used for statistical analysis, the significant differences were determined by one-way analysis of variance (ANOVA) and Duncan's multiple range test, and $p < 0.05$ was considered statistically significant. Data were obtained from triplicate experiments and data are expressed as the average value ± standard deviation.

3. Results and discussion

3.1. Proximate components of cornstarch

The proximate components of cornstarch extracted from two newly harvested corns at different after-ripening times were shown in Table 1. The contents of moisture, ash, protein, and fat in Zd958 and Xy335 cornstarch were very low with no significant changes during the whole postharvest ripening period ($p > 0.05$). At 60 d, the apparent amylose contents in Zd958 and Xy335 cornstarch were similar at 23.83 and 22.70 (g/100 g), respectively, with no significant difference compared with 0 d. Labuschagne et al. [24] reported that the contents of amylose stored at different temperatures for 12 months were lower than 20 (g/100 g), far lower than our results. The results showed that the purity of cornstarch was very high and the extraction method in this test was feasible.

3.2. Scanning electron microscope analysis of cornstarch

The microstructure characteristics of Zd958 and Xy335 cornstarch were observed by SEM with the results shown in Fig. 1. The images showed that the structures of Zd958 (Fig. 1A and a) and Xy335 (Fig. 1B and b) cornstarch are typical ellipsoids and polygonal, which were similar to the images observed by Cai et al. [25]. While polygonal particles may be the result of space restriction [13]. The surface of Zd958 and Xy335 cornstarch was smooth at 0 d with small pinholes on the surface of cornstarch granules. However, the surface of Zd958 and Xy335 cornstarch was clean with no obvious change in the structure during the postharvest ripening storage, indicating that the extraction method of cornstarch is feasible and the protein and fat were cleanly removed.

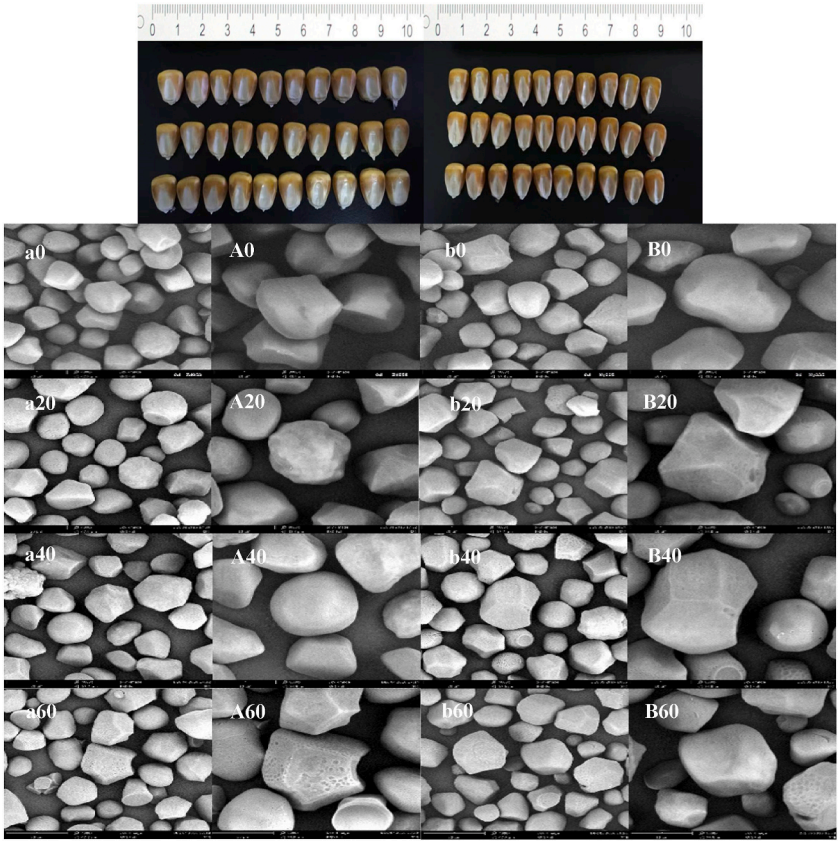

Fig. 1. SEM images of cornstarch. a, A (Zd958); b, B (Xy335). a, b (4000×); A, B (8000×). 0, 20, 40, 60 (storage time).

3.3. Molecular weight distribution and mass fraction of cornstarch

Light scattering technology is an important means to determine the molecular weight of polymers, and is currently recognized as the most effective method in the world to measure the value closest to the real molecular weight. More comprehensive and accurate polymer molecular weight information can be obtained by HPSEC-MALS-RI combined technology, which is widely used in the separation and analysis of biological macromolecules, especially in the determination of information related to the molecular weight of starch [26,27]. The Molecular weight distribution spectrum of Zd958 and Xy335 cornstarch obtained by HPSEC-MALS-RI chromatography was shown in Fig. 2A and B. The results showed that the molecular weight of cornstarch included three peaks identified from chromatography, and numbered peak 1, peak 2, and peak 3 according to their elution time. Three peaks have also been reported in native starch [19], in which peak 1 represented the high molecular weight part, mainly belonging to amylopectin with large molecular weight, peak 3 represented the low molecular weight part, mainly belongs to amylose with small molecular weight and fewer branches, peak 2 represented the intermediate molecular weight part between peak 1 and peak 2. The amylopectin molecular weight (peak 1) of Zd958 and Xy335 cornstarch at 60 d was significantly increased to 2.253×10^7 and 2.604×10^7 g/mol compared with 0 d (1.736×10^7 and 1.816×10^7 g/mol) (Table 2). The intermediate molecular weight (peak 2) and amylose molecular weight (peak 3) of Zd958 cornstarch were significantly decreased from 0.980 to 0.428 10^7 g/mol (0 d) to 0.624 and 0.344 10^7 g/mol (60 d), respectively, while the molecular weight of Xy335 cornstarch (peak 2 and peak 3) had little change. Our current results were slightly different from Lin et al., Sandhu et al., and Miao et al. [19,28,29]. The discrepancy may be attributed to different measurement methods, corn varieties, and growing and storage conditions. In addition, the mass fraction of three parts with different molecular weights of Zd958 and Xy335 cornstarch changed significantly at 60 d (Table 2), indicating that the molecular synthesis and rearrangement of cornstarch molecules occurred. The molecular weight distribution and the mass fraction of Zd958 cornstarch at 60 d were significantly different from that of Xy335 cornstarch. Therefore, changes in molecular weight distribution will also affect the molecular structure and some functional properties including pasting and textural properties.

3.4. X-ray diffraction analysis of cornstarch (XRD)

XRD technology is a commonly used method at present to study the crystal structure of starch, and the XRD spectrum is the basis for classification of starch crystal types [30]. The results of XRD for Zd958 and Xy335 cornstarch under postharvest ripening conditions were shown in Fig. 2C and D with the RC summarized in Table 3. XRD can provide information about crystal types including A-, B-, C-(A and B), and V-type (amylose-lipid complexes) [31]. In general, 2θ angles represent the crystal type of starch, and different crystal types of starch have specific diffraction peaks. Zd958 and Xy335 cornstarch showed typical A-type crystalline structure with obvious diffraction peaks at 15°, 17°, 18°, and 23° (2θ) in the spectrum (Fig. 2C and D). And both cornstarch showed similar XRD patterns during postharvest ripening, indicating that postharvest ripening would not lead to the transformation of crystalline polymorph. However, the diffraction peak intensities gradually increased with the extension of storage time, which means more structural crystallization. Similar XRD patterns were observed in wheat starch separated from the native and frozen dough [17].

The RC of Zd958 and Xy335 cornstarch was presented in Table 3, which also demonstrated an increasing trend. The RC values of Zd958 and Xy335 cornstarch under postharvest ripening conditions were significantly ($p < 0.05$) higher than that of 0 d (26.4% and 26.5%), ranged from 26.8% to 28.9% and 27.9%–29.8%, respectively. Thereby suggesting that postharvest ripening storage led to

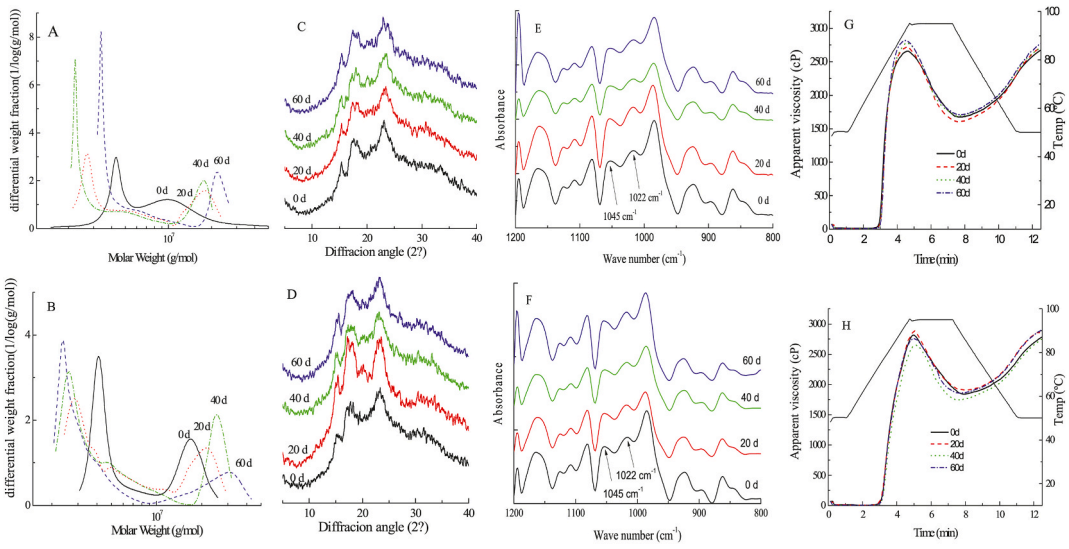

Fig. 2. Molecular weight distributions: A (Zd958), B (Xy335). X-ray diffraction. Spectrum: C (Zd958), D (Xy335). Deconvoluted FT-IR spectra: E (Zd958), F (Xy335). Pasting characteristics: G (Zd958), H (Xy335).

Table 2
Molecular weight distributions and mass fraction of cornstarch.

Varieties	Time	M_w (10^7 g/mol)			Mass fraction (%)		
	(d)	Peak 1	Peak 2	Peak 3	Peak 1	Peak 2	Peak 3
Zd958	0	1.736 ± 0.068^{g}	0.980 ± 0.034^{a}	0.428 ± 0.024^{a}	25.1 ± 0.5^{c}	49.6 ± 0.7^{a}	25.3 ± 0.4^{f}
	20	1.723 ± 0.006^{g}	0.574 ± 0.006^{d}	0.260 ± 0.016^{c}	33.6 ± 0.2^{a}	28.7 ± 0.5^{e}	37.7 ± 0.3^{c}
	40	1.905 ± 0.013^{e}	0.531 ± 0.020^{d}	0.246 ± 0.013^{c}	27.5 ± 0.3^{b}	35.3 ± 0.5^{c}	37.2 ± 0.5^{c}
	60	2.253 ± 0.015^{c}	0.624 ± 0.017^{c}	0.344 ± 0.013^{b}	27.2 ± 0.6^{b}	34.4 ± 0.4^{c}	38.4 ± 0.6^{c}
Xy335	0	1.816 ± 0.007^{f}	0.549 ± 0.015^{d}	0.241 ± 0.019^{c}	24.6 ± 0.3^{c}	45.9 ± 0.5^{b}	29.5 ± 0.2^{e}
	20	2.135 ± 0.018^{d}	0.706 ± 0.026^{b}	0.411 ± 0.021^{a}	32.2 ± 0.4^{a}	34.0 ± 0.4^{c}	33.8 ± 0.4^{d}
	40	2.407 ± 0.015^{b}	0.554 ± 0.026^{d}	0.331 ± 0.024^{b}	25.5 ± 0.6^{c}	30.5 ± 0.6^{d}	44.0 ± 0.5^{b}
	60	2.604 ± 0.019^{a}	0.530 ± 0.019^{d}	0.254 ± 0.010^{c}	24.2 ± 0.2^{c}	23.2 ± 0.2^{f}	52.6 ± 0.3^{a}

Values are the mean ± standard deviation, and different letters are significantly different between each column by $p < 0.05$.

Table 3
Changes in relative crystallinity (RC) and intensity ratio of 1045 cm^{-1}/1022 cm^{-1} (R1045/1022) of cornstarch.

Time	RC (%)		$R_{1045/1022}$	
(d)	Zd958	Xy335	Zd958	Xy335
0	26.4 ± 0.4^{b}	26.5 ± 0.4^{c}	0.828 ± 0.004^{c}	0.826 ± 0.003^{c}
20	26.8 ± 0.3^{b}	29.8 ± 0.2^{a}	0.831 ± 0.001^{c}	0.834 ± 0.001^{b}
40	28.9 ± 0.3^{a}	27.9 ± 0.3^{b}	0.837 ± 0.003^{b}	0.884 ± 0.004^{a}
60	28.8 ± 0.2^{a}	28.4 ± 04^{b}	0.843 ± 0.001^{a}	0.883 ± 0.004^{a}

Different letters are significantly different between each column by $p < 0.05$.

either the refinement and formation of crystallites or better orientation of double helices. And molecular chains of the starch, chain segments, and small structural units including side groups, branched chains, and chain segments moved to develop highly ordered crystalline structures [17]. Similar results have been described by Yang et al. [32]. In addition, the extensive rearrangement of starch chain segments in the amorphous regions may be another factor influencing the crystalline structure of starch [17].

3.5. Short-range molecular orders of cornstarch (FT-IR)

FT-IR spectroscopy, a powerful means to verify the chemical structure changes of starch molecules, has been widely used to characterize different polysaccharides. The ratio of absorbance at 1045 to absorbance at 1022 cm^{-1} ($R_{1045/1022}$) in the FT-IR spectrum can be applied to study the short-range ordered structure of starch particles [33]. The FT-IR deconvolution spectra of Zd958 and Xy335 cornstarch were in the range of 1200–800 cm^{-1} (Fig. 2E and F), and the values of $R_{1045/1022}$ were summarized in Table 3. The FT-IR spectra of Zd958 and Xy335 cornstarch under postharvest ripening conditions remained similar with 0 d, indicating that no new covalent bonds occurred during postharvest ripening storage (Fig. 2E and F). It was found that the $R_{1045/1022}$ values of Zd958 and Xy335 cornstarch under postharvest ripening conditions ranged from 0.831 to 0.834 to 0.843 and 0.884, respectively, were significantly ($p < 0.05$) higher than that of 0 d (0.828 and 0.826). Similar results were obtained in frozen wheat starch [17]. The greater the value of $R_{1045/1022}$, the higher the ordered degree. These findings demonstrated that postharvest ripening storage increased the linkages between starch chains and facilitated the rearrangement and packing of helical structures, resulting in more ordered molecular structures. In addition, the short-range ordered degree of cornstarch molecules may also increase due to the increased mobility of amylose. Therefore, the ordered degree of the short-range ordered structure of Zd958 and Xy335 cornstarch during postharvest ripening storage increased, which is consistent with the results of XRD.

Table 4
Pasting characteristics of cornstarch.

Varieties	Time (d)	PT (°C)	PV (cP)	BV (cP)	FV (cP)
Zd958	0	71.9 ± 0.3^{d}	2655 ± 12^{g}	981 ± 7^{d}	2743 ± 10^{g}
	20	72.8 ± 0.3^{c}	2717 ± 7^{f}	1114 ± 8^{a}	2734 ± 8^{g}
	40	72.7 ± 0.4^{c}	2781 ± 12^{d}	1095 ± 5^{b}	2771 ± 7^{f}
	60	72.7 ± 0.2^{c}	2817 ± 7^{c}	1109 ± 4^{a}	2841 ± 7^{c}
Xy335	0	72.7 ± 0.4^{c}	2835 ± 13^{b}	1065 ± 6^{c}	2800 ± 11^{e}
	20	73.6 ± 0.1^{b}	2892 ± 8^{a}	983 ± 6^{d}	2944 ± 11^{b}
	40	74.4 ± 0.2^{a}	2652 ± 8^{g}	909 ± 4^{e}	2817 ± 9^{d}
	60	74.4 ± 0.1^{a}	2760 ± 8^{e}	903 ± 3^{e}	2967 ± 9^{a}

Different letters are significantly different between each column by $p < 0.05$. Values are the mean ± standard deviation. PT (pasting temperature), PV (peak viscosity), BV (breakdown viscosity), FV (final viscosity).

3.6. Pasting characteristics analysis of cornstarch

Starch pasting properties are important processing characteristics of starchy food. It is valuable to the assessment and valuation of food processing and final food quality [34]. The pasting characteristics of Zd958 and Xy335 cornstarch were shown in Fig. 2G and H with the parameters summarized in Table 4. It showed that the pasting behavior of cornstarch was strongly influenced by the number of days after harvest. Pasting temperature (PT) is the temperature that starch particles begin to expand, and it showed that the PT values of Zd958 and Xy335 cornstarch under postharvest ripening conditions were significantly ($p < 0.05$) higher than that of 0 d (71.9 and 72.7), ranged from 72.7 °C to 72.8 °C and 73.6 °C–74.4 °C, respectively (Table 4). The increment may be related to the rearrangement of starch molecular chains (see Section 3.3) and the enhancement of long-range and short-range ordered molecular structures (see Sections 3.4 and 3.5). Moreover, the PT value of Xy335 cornstarch at 60 d was significantly higher than that of Zd958.

The peak viscosity (PV) value is the peak value of the starch granule when it swells to its maximum volume, which reflects the degree of granule swelling and water-binding ability, and determines the texture quality of the final product. The PV value of a starch paste is an important characteristic that distinguishes a given starch from other starch types [35]. PV of Zd958 cornstarch under postharvest ripening conditions increased significantly from 2655 (0 d) to 2817 cP (60 d), while PV of Xy335 cornstarch significantly decreased from 2835 (0 d) to 2760 cP (60 d). Final viscosity (FV) of Zd958 and Xy335 cornstarch increased significantly from 2743 to 2800 cP (0 d) to 2841 and 2967 cP (60 d), respectively. The changes in PV and FV were more obvious with the extension of postharvest ripening time. Our results were contrary to those of Wang et al. [17], who reported that PV and FV values of wheat starch isolated from native and frozen dough significantly decreased during frozen storage. The breakdown viscosity (BV) value of Zd958 cornstarch increased significantly compared with 0 d, while Xy335 cornstarch decreased significantly. The pasting properties of starch were influenced by amylose and lipid content and branch chain length distribution of amylopectin. The differentiation of starch pasting properties during postharvest ripening storage shifted the amylopectin chain length distribution to shorter branch chains; therefore, the starch past tended to increase over time [6]. In summary, Xy335 cornstarch had higher hot-paste stability than Zd958 cornstarch under postharvest ripening conditions.

3.7. Texture profile analysis (TPA)

TPA, a mechanical test developed by people to imitate the sensory evaluation of food texture, is an objective physical inspection of products and provides direct information on product quality. It is mainly used as a bridge between sensory evaluation and instrument analysis of food texture, and is widely used for its objective evaluation [36]. The change of TPA value reflects the change of molecular structure in gel. The texture profile of cornstarch gels including hardness, adhesiveness, gumminess, and springiness was analyzed after 24 h storage at 4 °C, with the results shown in Table 5. The hardness of starch, closely related to retrogradation, is an important parameter to estimate the retrogradation degree [37]. The result showed the hardness of Zd958 cornstarch under postharvest ripening conditions decreased significantly compared with 0 d, while Xy335 cornstarch did not change much. The hardness value verified the XRD results, indicating that different microstructures of cornstarch lead to different starch interactions and retrogradation tendencies. The adhesiveness results of Zd958 and Xy335 cornstarch during postharvest ripening storage we got, ranged from −37.31 to −23.21 and −55.28 to −36.1, increased significantly compared with 0 d (−106.97 and −98.63). It was reported that Low starch adhesiveness is beneficial in commercial applications, because the adhesiveness of gels on the lips or teeth may not be desirable [38]. The values of gumminess and springiness of Zd958 and Xy335 cornstarch at the end of postharvest ripening were similar and changed little compared with 0 d.

4. Conclusion

Results of this study revealed that the proximate components and apparent structure of Zd958 and Xy335 cornstarch did not change significantly during postharvest ripening for 60 d, except for the appearance of small pinholes on the surface. The changes in molecular weight distribution and mass fraction, as well as the increase in RC and $R_{1045/1022}$, suggested that postharvest ripening storage did not cause the crystal transformation of Zd958 and Xy335 cornstarch, and the cornstarch molecules underwent molecular synthesis and rearrangement to form highly ordered crystalline structures, resulting in the ordered structures increase of long-range and short-range molecules. As a result, the pasting characteristics and texture profiles of cornstarch were affected. This study can provide basic information for exploring the molecular basis of the physicochemical, structural, and functional properties of starch. However, the exact mechanism of explaining this structure-function relation needs to be further elucidated.

Author contribution statement

Yong Cao: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Xiujuan Wang: Performed the experiments; Wrote the paper.

Chengbin Zhao, Hao Zhang, Jingsheng Liu: Conceived and designed the experiments.

Mingzhu Zheng: Contributed reagents, materials, analysis tools or data.

Xiuying Xu: Analyzed and interpreted the data.

Table 5
Gel texture characteristics of cornstarch.

Varieties	Time (d)	Hardness (g)	Adhesiveness (g)	Gumminess (g)	Springiness (g·s)
Zd958	0	368.69 ± 22.05^{a}	-106.97 ± 4.36^{e}	159.66 ± 10.32^{c}	0.89 ± 0.03^{c}
	20	307.64 ± 14.91^{b}	-23.21 ± 2.19^{a}	153.98 ± 8.75^{c}	0.98 ± 0.04^{b}
	40	$305.76 \pm 9.76b^{c}$	-27.84 ± 3.26^{a}	210.58 ± 9.84^{a}	0.98 ± 0.03^{b}
	60	312.26 ± 12.36^{b}	-37.31 ± 1.40^{b}	153.42 ± 8.24^{c}	1.07 ± 0.04^{a}
Xy335	0	297.43 ± 10.43^{bc}	-98.63 ± 5.02^{d}	$162.71 \pm 8.66b^{c}$	0.96 ± 0.02^{b}
	20	281.30 ± 11.25^{c}	-39.29 ± 2.18^{b}	149.26 ± 6.45^{c}	0.97 ± 0.01^{b}
	40	308.24 ± 14.18^{b}	-36.1 ± 3.85^{b}	177.01 ± 7.85^{b}	0.96 ± 0.03^{b}
	60	308.83 ± 12.61^{b}	-55.28 ± 4.26^{c}	164.67 ± 8.52^{bc}	0.94 ± 0.02^{bc}

Different letters are significantly different between each column by $p < 0.05$.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare no conflicts of interest regarding the research, authorship, or publication of this article.

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