Structure, gelatinization, and digestion characteristics of starch from Chinese wild rice

Haifeng Zhang\textsuperscript{a,b}, Jiamin Su\textsuperscript{a}, Qiuyu Wang\textsuperscript{a}, Meng Yuan\textsuperscript{a}, and Chunmei Li\textsuperscript{a,b}

\textsuperscript{a}College of Tourism and Cuisine, Yangzhou University, Yangzhou, JP, P. R. China; \textsuperscript{b}Key Laboratory of Chinese Cuisine Intangible Cultural Heritage Technology Inheritance, Ministry of Culture and Tourism, Yangzhou University, Yangzhou, JP, P. R. China

ABSTRACT
Two wild rice starches were isolated from Erhai in Dali, Yunnan Province (EWR) and Xinghua in Taizhou, Jiangsu Province (XWR), China, and compared with black rice (BR) starches, its structure, gelatinization and starch digestibility in vitro were studied. The results showed that the apparent amylose content of starches in EWR and XWR was 19.82\% and 20.33\%, respectively. The starch granules were irregular polygons and all were A-type crystals, with relative crystallinity of 25.6\%--26.65\%, similar short-range ordered structure and layered structure, and the thickness of the semi-crystalline layer ranged from 9.82 nm to 9.97 nm. XWR and EWR starches had exhibited the same gelatinization temperature range, enthalpy of gelatinization (\(\Delta H_{\text{gel}}\)) and swelling power, but XWR starches was higher than EWR in the gelatinization temperature and lower than EWR in the solubility. The rapidly digestible starch (RDS) content of wild rice starches in the two regions was low, only 3.63\% and 37.32\%, whether it was raw starches or gelatinized starches. After gelatinization, the RDS and slowly digestible starch (SDS) content were significantly increased and the resistant starch (RS) content was decreased, but the RS content was still higher than the common grains. Therefore, the wild rice starches are more suitable for processing and producing resistant starch products. Extracting starch from Chinese wild rice can provide guidance and reference for its application in edible and non-edible products, and promote the development and utilization of Chinese wild rice.

Abbreviations: EWR, wild rice from Erhai in Dali, Yunnan Province; XWR, wild rice from Xinghua in Taizhou, Jiangsu Province; RDS, rapidly digestible starch; SDS, slowly digestible starch; RS resistant starch; TS, total starch; \(T_o\), onset temperature of gelatinization; \(T_p\), peak temperature of gelatinization; \(T_c\), conclusion temperature of gelatinization.

Introduction
Wild rice (\textit{Zizania spp.}), as an essential aquatic cereal crop, mainly includes four species of \textit{Zizania latifolia} in East Asia and \textit{Zizania aquatica}, \textit{Zizania palustris}, and \textit{Zizania texana} in North America.\textsuperscript{[1]} Chinese wild rice is the Caryopsis of \textit{Zizania latifolia}. \textit{Zizania latifolia} belongs to the genus \textit{Zizania}, the family Poaceae, which is widely distributed in rivers, lakes, ponds and other waters all over China (Figure 1a).

Chinese wild rice, also known as Diaohu, Anhu, Jiao-rice, etc. was recorded as early as the Zhou Dynasty more than 3,000 years ago, and it was also mentioned in the Confucian classic Book of Rites. Since the Tang Dynasty, Chinese wild rice has also been used as a traditional Chinese medicine to treat hyperglycemia and gastrointestinal diseases.\textsuperscript{[3]} Compared with North American wild rice, Chinese wild rice has a smaller
length and grain size (Figure 1a), rich flavor and rich nutrition after being cooked, so it enjoys the reputation of “caviar in grain”.[4] However, as people’s food sources become more and more abundant, Chinese wild rice gradually disappears on people’s tables due to low production and complicated processing. On the contrary, because of its unique flavor and rich nutrients, North American wild rice has been gradually used in many food products since the 1990s.[5,6]

Studies have shown that Chinese wild rice is rich in nutrients such as protein, vitamins B1, B2, and E, and minerals. It is a whole grain food with high nutritional value,[7] superior to other grains such as rice, barley and corn.[4,8] In addition, it also contains a large number of bioactive substances like phenolic compounds and sterols, which have various healthcare effects such as antioxidation, regulating intestinal flora, improving insulin resistance, reducing the inflammatory response and preventing atherosclerosis.[9–12]

Starch is a carbohydrate widely existing in cereals, potatoes, beans and other plants. It is mainly composed of amylose and amyllopectin. Its constituent unit is D- glucose, and its molecular formula is (C6H10O5)n.[13] Starch from different sources has different structural characteristics, which leads to differences in its properties. It can be used as edible raw materials and as industrial materials in medicine, textile, chemistry, and other fields. Whether starch is used in edible products or non-edible

Figure 1. Image of Zizania latifolia (a), they are growing by the lake; the Zizania latifolia were harvested but unhulled and has a long awn; Chinese Wild rice, which is slender and dark brown in color. Location and temperature zone of wild rice in Erhai and Xinghua (b).
products, it is necessary to understand the relationship between its structure and properties. Some studies have reported starch’s physical and chemical characteristics in North American rice, including its micro-morphology, amylose content, crystal type, thermal characteristics, etc. Among them, it is found that the starches content in North American wild rice is about 60%-65%, and the average amylose content is 17.33%. The gelatinization temperature of starches is similar to brown rice starches but higher than wheat starches, and its solubility and swelling power are higher than wild rice, so it belongs to Type-A. There are no reports about Chinese wild rice starches’ physicochemical properties and in vitro digestibility. This study collected wild rice from Erhai in Dali, Yunnan Province (EWR) and Xinghua in Taizhou, Jiangsu Province (XWR), China. The geographical environment and climate of the two major producing areas are different, as shown in Figure 1b. Erhai in Dali is located in the southwest plateau of China, with a subtropical monsoon climate. In contrast, Xinghua in Taizhou is located in the eastern plain of China, with a subtropical monsoon humid climate. Therefore, the structure, gelatinization and digestion characteristics of wild rice starches in these two regions were studied and compared with black rice (BR) starches. The contents of various nutritional elements in BR are higher than rice, and it has excellent nutritional value and medicinal properties, which is similar to Chinese wild rice. And because the outer skins of both of them are colored, they contain a lot of bioactive components. This study provide guidance and reference for applying Chinese wild rice starches in edible and non-edible products and promoting the development and utilization of Chinese wild rice.

Materials and methods

Samples

EWR was harvested in Erhai, Dali City, Yunnan Province and XWR was harvested in Xinghua, Taizhou City, Jiangsu Province in 2021. Mature and sound wild rice kernels were obtained by manual unshell decorticate. BR was produced in Yangxian County, Hanzhong, Shaanxi Province and purchased in 2021.

Starch extraction

Starch extraction was carried out according to the method described in Wang et al. with slight modifications. Wild rice kernels (15 g) were soaked in 75 mL of sodium hydroxide solution (0.1%, w/v) 16 h at 4°C, using a homogenizer for 2 min to ground into the slurry. The homogenate was sifted through a screen 80-, 200- and 400- mesh respectively. The filtered liquid was centrifuged at 4000 g for 15 min, then the supernatant was decanted and the upper taupe brown layer was scraped off with a scraper. The precipitate was washed by water, centrifuging and scraping the upper taupe brown layer, repeat the above steps until the precipitate is pure white, dried at 45°C overnight. Starch granules were grinded and sifted through a sieve of 80-mesh. Black rice starches were extracted by the same method.

Chemical composition

The content of moisture, protein, ash and total starch were measured according to the official methods (934.01, 954.01, 942.05 and 996.11, respectively) of the AOAC. The apparent amylose content was measured according to He et al. The percent amylose content was determined by the iodine binding assay. 10 mg of Chinese Wild rice starch sample was first suspended in 100 μL of 95% ethanol, then dissolved in 1 ml of 1 mol/L NaOH and diluted 10 times with water. The above solution was neutralized with 0.1 mol/L HCl and diluted to a final 0.25 mg/ml as starch stock solution. Then mix 0.2 ml of starch stock solution with 3.6 ml water and 0.2 ml of KI-12 solution, put at room temperature for 30 min. Finally, the absorbance value was measured at 510 and 620 nm. The content of amylose was calculated according to the following formula.
Amylose(%) = A_{620} - A_{510} + 0.0542/0.3995 \times 100

**Scanning electron microscopy (SEM)**

Images of starch granules were acquired using a Gemini SEM 300 (ZEISS, Germany) under an accelerating voltage of 5 kV and at 3000 multiple magnifications. Starch granules were attached to the aluminum stub column with double-sided conductive tape before coating with a gold film.

**X-ray diffraction (XRD)**

X-ray patterns were performed with a D8 Advance X-ray diffractometry (Bruker-AXS, Germany) at 40 kV and 40 mA Cu-Kα radiation. The scanning region (2θ) was from 3 to 40° at 0.02° step size with a count time of 0.2 s. The relative crystalline was calculated by MDI Jade 6 software.

**Fourier-Transform infrared spectrometry (FTIR)**

The short-range ordered structure of starches was measured on Cary 670 FTIR spectrometer (Varian, America). Starch granules were mixed with potassium bromide and pressed them into thin slices by a mold, then added them to the sample cell. Scanned from 4000 cm\(^{-1}\) to 400 cm\(^{-1}\) with 4 cm\(^{-1}\) resolution and 48 scans. The spectrum was corrected by a baseline between 1200 cm\(^{-1}\) and 800 cm\(^{-1}\) and the deconvolution was performed using OMNIC software, a half-width and a resolution enhancement factor of 19 cm\(^{-1}\) and 1.9.

**Small angle X-ray scattering (SAXS)**

Starch suspension (1%, 0.0500 g/5 mL) was balanced overnight at room temperature, centrifuged at 4000 r/min for 10 min, then the supernatant was decanted to obtain starch slurry for later use. The lamellar structures of starch samples were tested using a NanoSTAR small-angle X-ray scattering machine (Bruker-AXS, Germany). The electric voltage was set at 50kV and current was set at 0.6 mA, The X-ray source radiated by Cu-Kα had a wavelength of 0.154 nm. DIFFRAC plus NanoFit software was used to processed the data, the thickness of crystalline lamellae was calculated using the equation 

\[ D = \frac{2\pi}{\lambda} \times \frac{1}{\sin(\theta)} \]

**Thermal properties (DSC)**

The thermal properties of starch were measured according to the method described by Hoover et al. [17] with slight modifications. Starch granules (0.0030 g) was weighed in an aluminum pan and distilled water (11 μl) was added. Then the aluminum pan was sealed and balanced at room temperature for 16h. The sample pan and the empty pan as the reference pan were scanned using a differential scanning calorimeter (NETZSCH, Germany) from 20 to 120 °C at 10°C/min. The DSC characteristics were analyzed from onset temperature of gelatinization (To), peak temperature of gelatinization (Tp), conclusion temperature of gelatinization (Tc) and enthalpy of gelatinization [ΔHgel].

**Solubility and swelling power**

The solubility and swelling power was measured according to Li and Yeh [24], 1% starch suspension (0.0500 g/5 mL) was placed into plastic tubes and placed into water bath from 55°C to 95°C (10°C increments) respectively and heated for 30 min with vortexing every 5 min. Then, the suspension was cooled at room temperature and centrifuged at 4000 g for 20 min. The supernatant was separated and
dried at 105°C to constant weight and weighed the sediment. The initial weight of the starch (W), the weight of the soluble starch (A) and the weight of sedimental paste (P) were used to calculate the solubility and swelling power of the starch.

\[
Solubility(\%) = \frac{A}{W} \times 100
\]

\[
Swellingpower(g/g) = \frac{P \times 100}{W \times (100 - Solubility)}
\]

**In vitro starch digestibility**

In vitro starch digestion of raw starches and gelatinized starches were carried out according to the method described in Englyst et al.\(^{[25]}\) with modifications. The procedure of gelatinized starch was carried out according to 0.2 g starch was dispersed in 15 mL of sodium acetate buffer solution (0.2 M, pH 5.2) and placed into boiling water bath for 30 min with vortexing every 5 min. After cooling down, the sample was balanced in a SHZ-82 stable temperature horizontal shaking bath (PINGXUAN, Shanghai, China) at 37°C and 160 rpm/min for 5 min before added pancreatin (4 mL, 290 U.mL\(^{-1}\)) and amylolucosidase (1 mL, 15 U.mL\(^{-1}\)). Digesta (0.5 mL) was collected at 0, 20, 120 and 180 min, after which 4.5 mL of absolute ethanol was immediately added to deactivate the enzymes. Then centrifuged at 4000 rpm/min for 5 min. The procedure of raw starches was carried out according to 0.5 g of starches and 0.05 g of guar gum was added, and the subsequent steps were the same except that they did not need to be gelatinized in a boiling water bath for 30 min. The glucose generated contents was determined using DNS method. The rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) were obtained according to the following equation.

\[
RDS(\%) = \frac{(G_{20} - FG) \times 0.9}{TS} \times 100
\]

\[
SDS(\%) = \frac{(G_{120} - G_{20}) \times 0.9}{TS} \times 100
\]

\[
RS(\%) = \frac{[TS - (RDS + SDS)]}{TS} \times 100
\]

where FG, G20, G120 are the the glucose generated contents of hydrolysis at time 0, 20, 120 (min), respectively, TS is the total starch contents.

**Statistical analysis**

All the results were expressed as means ± standard deviation of at least three measurements. The data was analyzed by one-way ANOVA and Duncan’s multiple comparison in SPSS 19.0 software, the difference was statistically significant with P < 0.05.

**Results and discussion**

**Chemical composition**

The chemical composition of the starches extracted from EWR, XWR and BR are summarized in Table 1. There was no significant difference in the moisture content of EWR and XWR starches, and the content was in the range of 10.76%-11.21%, which was higher than BR starches. The upper layer of gray-brown material scraped off during starch extraction was some non-starchy material such as protein, fat and
minerals, so the residual protein and ash content of EWR and XWR starches were less, where the protein content of EWR and XWR starches were higher than BR starches, possibly because the protein content of EWR and XWR was higher than BR.\textsuperscript{[4,26]} Also, the protein removal is affected to some extent by the higher content of straight-chain starch in the wild rice, which has a higher binding capacity to the protein.\textsuperscript{[27]} The total starch content extraction rate reached 90.06%, which indicates that the starch extraction process was efficient. The apparent amylose content in the two wild rice starches was significantly different (P < .05), with the highest content of 20.33% in XWR and 19.82% in EWR, and the lowest apparent amylose content of 15.49% in BR. According to the content of amylose, it can be divided into non-waxy starch (17–31.9%), low amylose starch (7.8–16%) and waxy starch (0–3.5%). It is evident that the EWR and XWR starches are a non-waxy starch, while the BR starches are a low amylose starch. Apparent amylose starch content is an important characteristic that affects the quality of starch\textsuperscript{[28]} and affects the physicochemical and functional properties of starch, among others, especially playing an important role in their pasting process.\textsuperscript{[29]}

**Table 1.** Composition of starches from EWR, XWR and BR.

| Starch | Moisture (g/100 g) | Protein (g/100 g) | Ash (g/100) | Total starch (g/100 g) | Apparent amylose (%) |
|--------|--------------------|-------------------|-------------|------------------------|---------------------|
| EWR    | 11.21 ± 0.16\textsuperscript{a} | 0.55 ± 0.01\textsuperscript{a} | 0.53 ± 0.00\textsuperscript{c} | 90.32 ± 0.71\textsuperscript{a} | 19.82 ± 0.00\textsuperscript{a} |
| XWR    | 10.76 ± 0.18\textsuperscript{a} | 0.58 ± 0.01\textsuperscript{a} | 0.59 ± 0.00\textsuperscript{b} | 89.36 ± 0.46\textsuperscript{a} | 20.33 ± 0.00\textsuperscript{a} |
| BR     | 9.11 ± 0.23\textsuperscript{b} | 0.51 ± 0.04\textsuperscript{b} | 0.84 ± 0.00\textsuperscript{b} | 90.49 ± 0.27\textsuperscript{b} | 15.49 ± 0.08\textsuperscript{c} |

All the experiments were in triplicate and data were expressed as mean value ± SD (n = 3). Values with different letters in the same column show significant difference at p < 0.05.

**Morphology of starch granule**

Figure 2a-c shows the morphology of starch granules extracted from EWR, XWR and BR. The morphological variability of starch granules from similar or the same family was not evident. Hence, EWR and XWR starches showed a similar granule shape as BR starches, except that the starch granule size was slightly smaller than BR starches. The grains of EWR and XWR starches were irregularly polygonal and angular, which may be related to its high amylose starch content,\textsuperscript{[30]} and most of the starch granules had smooth surfaces with cereal specific tiny pores.\textsuperscript{[17,18,20]} However, some starch granules still had some fine particles attached to their surfaces, which may be due to some non-starchy substances such as proteins or lipids left during the starch extraction process.\textsuperscript{[29]}

**Crystalline structure of starch**

The crystal structure of starch can be analyzed using XRD. The crystal types of starch can be generally classified as type A, type B, and type C. Among them, cereal starch had a type A crystal, with the diffraction peaks at 15°, 17°, 18°, and 23°.\textsuperscript{[31]} As shown in Figure 3, the XRD patterns of EWR and XWR starches were generally similar. EWR starches showed diffraction peaks at about 15.28°, 17.04°, 18.02°, 23.02°, and XWR starches showed diffraction peaks at about 15.01°, 17.06°, 18.06°, 23°, BR starches showed diffraction peaks at about 15.14°, 17.08°, 18.08°, 23.1°, indicating they were type A starches.

The relative crystallinity of EWR and XWR starches was significantly different (P < 0.05). The relative crystallinity of EWR starches was 26.65%, and that of XWR starches was 25.60%, slightly lower than BR starches (27.5%). In general, the relative crystallinity is negatively correlated with amylose content and positively correlated with starch granules’ size.\textsuperscript{[32,33]} Compared with BR starches, the low relative crystallinity of EWR and XWR starches might result from their high apparent amylose content and small starch granules.
Short-Range ordered structure of starch

FTIR spectra are often reflected for the determination of the short-range ordered structure of starch.\cite{34} The absorbance peak near 1047 cm\(^{-1}\) is related to order/crystalline region, and that near 1022 cm\(^{-1}\) is related to amorphous region. The absorbance peak near 995 cm\(^{-1}\) is related to water-starch interactions.\cite{35} Usually, the ratios of 1047/1022 cm\(^{-1}\) and 1022/995 cm\(^{-1}\) are widely used to quantify the ratio of ordered area and amorphous area in starch.\cite{36} Starches from EWR, XWR and BR showed a similar FTIR spectrum at 1200–800 cm\(^{-1}\) in Figure 4a, and both had typical absorption peaks of starchy foods. Figure 4b

Figure 2. SEM of starches from EWR (a), XWR (b) and BR (c).
showed the absorbance ratios at 1047/1022 cm\(^{-1}\) and 1022/995 cm\(^{-1}\) for the different starches. There was no difference in the ratio of 1047/1022 cm\(^{-1}\), and the ratio ranges from 0.74% to 0.80%, which proved that EWR, XWR and BR starches had similar short-range ordered structures in the outer region of the granules. Among them, the ratio of XWR starches was the lowest, which represented the lowest order, followed by EWR starches. In the ratio of 1022/995 cm\(^{-1}\), there was no significant difference between EWR and XWR starches, but there was a significant difference (\(P < 0.05\)) compared with BR starches, and the ratio ranged from 1.04% to 1.39%. Among them, the ratio of EWR starches was the largest, which represented the highest degree of combination with water. Studies have shown that the content of amylose was affected the ordered degrees of starches.\(^{[37]}\) In addition, the relative crystallinity was positively correlated with the ordered degrees of starches.\(^{[38]}\) This was consistent with the resulted of our research.

**Lamellar structure of starch**

The information of the lamellar structure of starch grains, which consisted of alternating amorphous and crystalline regions, can be measured by small-angle X-ray scattering (SAXS) spectroscopy.\(^{[39]}\) Figure 5 shows the SAXS spectra of EWR and XWR starches and BR starches. EWR and XWR starches showed scattering peaks at a scattering vector of about 0.064 Å\(^{-1}\), and there was no significant difference in peak intensity, ranging from 128.65 to 131.80. The thickness of the semi-crystalline layer (D) also showed no significant differences, ranging from 9.82 nm to 9.97 nm. However, compared with BR starches, there were significant differences in peak intensity and semi-crystalline layer thickness (\(P < 0.05\)). The scattering peak of BR starches appeared at the scattering vector of about 0.067 Å\(^{-1}\), and the peak intensity was 161.55, which was higher than EWR and XWR starches. The semi-crystalline layer thickness (D) was 9.38 nm, slightly lower than EWR and XWR starches. The peak intensity reflects the difference of electron density between the crystalline and amorphous regions, which indicated that the ratio of amorphous region to crystalline region of EWR and XWR starches were smaller than BR starches. The peak position reflects the layer’s size, and the peak position’s shift may be due to the differences in starch from different plants.\(^{[16]}\) It has been reported that peak intensity is negatively related to amylose content, while semi-crystalline layer thickness is positively correlated with amylose content. In addition, the thickness of semi-crystalline layer is usually related to the arrangement of amylose and amylopectin and the arrangement of different amylopectin molecules in crystalline and amorphous regions.\(^{[40,41]}\)
Figure 4. FTIR spectra (a), 1047/1022 and 1022/995 ratios (b) of starches from EWR, XWR and BR.
**Thermal properties of starch**

Table 2 shows the results of DSC measurement of the thermal parameters of EWR, XWR and BR starches. T₀, Tₚ and Tₖ of XWR starches were 64.63, 70.63 and 76.1°C, respectively, which were significantly higher than EWR starches of 60.87, 67.6 and 73.77°C (P < 0.05), but there was no significant difference in ΔHgel, which was 7.66 J/g and 8.73 J/g, respectively. Compared with BR starches, the T₀ of EWR and XWR starches were respectively 2.7 and 6.46°C higher than BR starches, and Tₚ was respectively 2.8 and 5.83°C higher than BR starches, and Tₖ was respectively 2.94 and 5.27°C higher than BR starches, and there was a significant difference (P < 0.05), probably because their amylose content was higher than BR starches. It has been reported that the gelatinization temperature being positively related to amylose content, because starch with high amylose content requires a higher temperature to destroy its internal structure. Figure 5. SAXS spectra of starches from EWR, XWR and BR.

**Figure 5.** SAXS spectra of starches from EWR, XWR and BR.

**Table 2.** Thermal properties of starches from EWR, XWR and BR.

| Starch | T₀ (°C) | Tₚ (°C) | Tₖ (°C) | ΔH (J/g) |
|--------|---------|---------|---------|----------|
| EWR    | 60.87 ± 0.09ᵇ | 67.60 ± 0.15ᵇ | 73.77 ± 0.07ᵇ | 8.73 ± 0.11ᵇ |
| XWR    | 64.63 ± 0.20ᵃ | 70.63 ± 0.03ᵃ | 76.10 ± 0.25ᵃ | 7.66 ± 0.76ᵇ |
| BR     | 58.17 ± 0.09ᶜ | 64.80 ± 0.84ᶜ | 70.83 ± 0.77ᶜ | 9.39 ± 0.18ᵃ |

All the experiments were in triplicate and data were expressed as mean value ± SD (n = 3). Values with different letters in the same column show significant difference at p < 0.05.
**Solubility and swelling power of starch**

In the crystalline and amorphous regions of starch granules, the degree of bonding between amylose and amyllopectin can be evaluated by the swelling powers and solubilities of starches, and the interaction between starches and water was of great significance to the study of the processing characteristics of starchy foods.\[46,47\] Figure 6 showed the swelling powers and solubilities of EWR, XWR and BR starches at different temperatures. It can be seen from Figure 6a that the solubility increased of the three starches with increasing heat temperature. At 55°C, the solubility of EWR and XWR starches was 1.99% and 2.39% respectively, which had no significant difference and was slightly lower than BR starches. When the temperature was in the range of 55°C to 65°C, the solubility of EWR starches began to increase rapidly. When the temperature reached 65°C, the solubility of EWR starches was 4.98%, which was significantly higher than XWR and BR starches (P < 0.05). When the temperature rised from 65°C to 75°C, the solubility of EWR starches became flat, while the solubility of XWR starches began to increase rapidly. This situation may be due to the difference of To of EWR and XWR starches, and when the gelatinization temperature was reached, the starch began to gelatinize, and the solubility also increased. When the temperature reached 95°C, the solubility of XWR starches was 15.37%, which was significantly higher than EWR and BR starches (P < 0.05). Studies have shown that when starch was gelatinized by heating, amylose will be released, thus increasing its solubility.\[31\] It can be seen from Figure 6b that the swelling power of the three starches was positively correlated with temperature. When the temperature was from 55°C to 65°C, the swelling power of EWR and XWR starches increased rapidly from 3.53 to 7.84% and 2.67 to 7.34%, and the difference was significant (P < 0.05). When the temperature reached 75°C, the swelling power of the three starches had no significant difference, which was 9.84, 10.09 and 9.37% respectively. When the temperature raised from 85°C to 95°C, the swelling power of EWR and XWR starches increased rapidly again, to 17.87 and 16.54%, and the swelling power of EWR starches was slightly larger than XWR and BR starches, but the difference was not obvious. Swelling power reflected the interaction between starches and water, which was beneficial to the application of wild rice in product processing. Different heating temperatures can be selected according to the gelatinization degree of wild rice.

**Digestion properties of starch**

Starch can be divided into RDS, SDS and RS according to the time of glucose release from starch digestion. The content of the three starches can determined the difficulty of starch digestion.\[24\] Table 3 shows the digestion properties of EWR, XWR and BR starches in raw starch and gelatinized starch. When three kinds of starch were digested directly without gelatinization, the RDS content of EWR and XWR starches only 3.61%, which was 1.06% lower than BR starches. In SDS+RS content, the content of EWR and XWR
Table 3. Digestion properties of raw and gelatinized starches from EWR, XWR and BR.

| Source | Raw Starch | Gelatinized Starch |
|--------|------------|--------------------|
|        | RDS (%)    | SDS (%)            | RS (%)    | RDS (%) | SDS (%) | RS (%) |
| EWR    | 3.61 ± 0.14<sup>b</sup> | 25.67 ± 0.73<sup>b</sup> | 70.72 ± 0.59<sup>b</sup> | 35.24 ± 0.36<sup>c</sup> | 49.43 ± 0.20<sup>a</sup> | 15.33 ± 0.16<sup>a</sup> |
| XWR    | 3.65 ± 0.05<sup>b</sup> | 28.08 ± 0.01<sup>a</sup> | 68.27 ± 0.06<sup>c</sup> | 39.39 ± 0.11<sup>b</sup> | 45.35 ± 0.74<sup>b</sup> | 15.25 ± 0.85<sup>a</sup> |
| BR     | 4.69 ± 0.01<sup>a</sup> | 21.03 ± 0.02<sup>c</sup> | 74.29 ± 0.03<sup>b</sup> | 41.41 ± 0.47<sup>c</sup> | 47.78 ± 1.40<sup>b</sup> | 10.81 ± 0.93<sup>b</sup> |

All the experiments were in triplicate and data were expressed as mean value ± SD (n = 3). Values with different letters in the same column show significant difference at p < 0.05.

starches was higher than BR starches, and there was a significant difference (P < 0.05). Compare with raw starches, after starch gelatinization, the RDS and SDS contents of EWR starches increased by 31.63% and 23.76% respectively, the RS content decreased by 55.39%, the RDS and SDS contents of XWR starches increased by 35.74% and 17.27% respectively, and the RS content decreased by 53.02%. The gelatinized EWR and XWR starches were lower than gelatinized BR starches by 6.17% and 2.02% respectively, and the RS content was higher than BR starches by 4.52% and 4.44%, but there was no significant difference in SDS content among them. It has been reported that the content and proportion of amylose and amylopectin were essential factors that affected the digestion and absorption of starch. Amylose is more challenging to digest than amylopectin in the human body to prolong the digestion time, reduce the glucose absorption rate, and be more conducive to the stability of postprandial blood sugar. In addition, RS belongs to starch that can’t be digested and absorbed by human small intestine. Foods with high RS content can delay postprandial blood sugar rise and improve lipid composition, and play a certain role in preventing and treating diabetes and obesity. Feeding wild rice to rats with lipid metabolism disorder induced by high-fat diet can obviously reduce their blood lipid and improve the low-grade inflammatory state of hyperlipidemia. The RS content of EWR and XWR starches was slightly higher than BR, buckwheat and quinoa starches, so it was suitable for processing producing resistant starch products.

**Conclusion**

In this paper, the physical and chemical properties of EWR and XWR starches did not differ greatly due to different regions and climates. Both of them have the structure of Gramineae starch, and have similar starch granules with angular irregular polygons. Although they were both A-type crystals, the relative crystallinity of EWR starches was higher than XWR starches. In addition, the short-range ordered structure and layered structure of EWR and XWR starches were similar, but there was no significant difference. In terms of physical and chemical properties, the purity of EWR and XWR starches extracted can reach 89.84%, with higher amylose content and less non-starch substances (protein, ash), but the gelatinization temperature of XWR starches was higher than EWR starches. And the solubility and swelling power increased with the increase of temperature, which led to the difference of their solubility due to the difference of T<sub>g</sub>. After gelatinization, the RDS and SDS contents of EWR and XWR starches were significantly higher than without any treatment, and the RS content was significantly reduced. The experimental results can provide theoretical guidance and data support for the processing of Chinese wild rice starches as a special food product in a specific field and the product development and application in other related fields.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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