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Influence of high natural field temperature during grain filling stage on the morphological structure and physicochemical properties of rice (*Oryza sativa* L.) starch

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ABSTRACT

This study investigated the effects of natural high temperature in the field during grain filling stage on the morphological structure and physicochemical properties of rice starch. High natural field temperature during rice grain filling stage resulted in poor processing and appearance quality, higher gelatinization properties including gelatinization temperature, gelatinization enthalpy, swelling power, and water solubility due to the reduction of amylose content. High temperature decreased the setback and trough viscosities, and increased breakdown, implying that the pasting properties were slightly better. High temperature did not change the starch crystalline type, while it significantly affected relative crystallinity, as well as pitting and unevenness on the surface of the starch granules with lower granule size. The above results imply that high temperature can degrade cooking and eating quality, and increase pasting properties of starch slightly.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops. As the improving of people's living standard, consumers have put forward higher demands for rice quality (Kong, Zhu, Sui, & Bao, 2015). Rice quality includes processing quality, appearance quality, eating and cooking quality (ECQ), and nutritional quality. Consumers are particularly concerned about ECQ, which is closely associated with rice starch characteristics such as amylose content, thermal characteristics, pasting property, and so forth (Calingacion et al., 2014). Starch is the major component of rice grain, accounting for more than 80% of its total constituents, and the primary substance metabolized for energy derived from rice. Rice starch consists of glucose homopolymers formed by dehydration and condensation: amylose (linear α-1, 4-polyglucan) and amylopectin (α-1, 6-branched-polyglucan). The morphological structure and physicochemical properties of rice starch are the major factors influencing rice quality. In previous study, the amylose content, gelatinization temperature (GT), pasting property, water solubility index, and swelling power were often used to evaluate rice ECQ (Tian et al., 2009).

In addition to genotypic differences, the morphological structure and physicochemical properties of rice starch are influenced by environmental factors. Extreme high-temperature events are becoming more frequent under the influence of the global warming trend. Conditions above certain temperatures optimal for rice growth seriously affect the physicochemical properties of rice starch (Chen et al., 2017). In particular, high temperature at grain filling stage has the greatest influence on rice quality, causing a high rate of chalky-rice, high degree of chalkiness and low head-milled rice rate (Zhang et al., 2016). Moreover, high temperature at grain filling stage also increases gelatinization temperature and significantly affects pasting property of starch (Zhang, Liao, Li, & Cai, 2016). Amylose content is thought to be an important factor affecting rice quality. At present, there are three reported hypotheses about the effect of high temperature on amylose content: 1) that high-temperature reduces amylose content (Lin et al., 2010; Umemoto & Terashima, 2002); 2) that high-temperature increases amylose content (Zhang et al., 2013); and 3) that the effects of high temperature on amylose content are cultivar-dependent, meaning that amylose content increases for cultivars with intrinsically high amylose content, while it decreases for those with intrinsically low amylose content (Zhong, Cheng, Wen, Sun, & Zhang, 2005).

Some studies have been conducted on the effect of high temperature

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in the filling stage on rice quality. For example, Deng et al. (2015) showed the optimal daily mean temperature for rice grain filling ranged from 22 to 27 °C in the grain filling stage, above which rice grew adversely. Wakamatsu, Sasaki, Uezono, and Tanaka (2007) reported that an average temperature of 27 °C or higher increased white-based, white-back kernel during 20 days after heading. Thitisaksakul, Jiménez, Arias, and Beckles (2012) showed that daily average temperature higher than the optimum temperature for rice growth easily caused lower amylose content and higher long-chain amylopectin content, which greatly influenced the ECQ of milled rice. Yamakawa, Hirose, Kuroda, and Yamaguchi (2007) found that the elevated temperature in the filling period increased chalky grain appearance, and further studies showed that the higher chalkiness might be caused by the change in amylopectin structure (Yamakawa & Hakata, 2010). Previous studies reported that high temperature during the grain filling stage could increase the gelatinization temperature and gelatinization enthalpy. Because the pasting enthalpy of starch was negatively correlated with amylose content, the increase in pasting enthalpy at high temperature might be related to the decrease in amylose content (Kong et al., 2015). Further studies found that high temperature during grain filling could change the crystalline structure and the component of starch and result in poor ECQ for early-season indica. According to microscopic observation of the chalky part, grains ripened during high temperature displayed numerous loosely packed starch granules, which caused wider spaces that reflected light randomly and promoted chalky formation (Cao et al., 2015; Geigenberger, 2011; Zakaria, Matsuda, Tajima, & Nitta, 2002).

Although many studies have been reported for the effect of high temperature at the filling stage on rice starch properties, most experiments have been performed in temperature-controlled growing chambers or on the basis of model construction. However, the rice growing environments are different between natural field and artificial climate chamber. Meanwhile, most studies have focused on the milling and appearance quality, and only a few papers have reported the changes in rice starch properties under high temperature at the filling stage. Hence, further researches should be performed to elucidate the effects of naturally high temperatures in the field on the morphological structure and physicochemical properties of rice starch during the filling stage to provide more reliable and practical data to breeders. The study was carried out with different natural high temperatures via sowing on different dates. Automatic temperature and humidity recorders (HOBO, Onset Computer Corp., Bourne, MA, USA) were installed in the field to measure the real-time temperature. The purpose of this study was to identify the effects on starch properties in rice grains that have been subjected to high temperature at the grain filling stage. The results can provide more comprehensive and practical data to breeders.

2. Materials and methods

2.1. Plant materials

Six rice varieties that have been widely popularized in production were used as plant materials for this experiment: Huanghuazhan (high-temperature-tolerant) (Duan, Tang, Ju, Liu, & Yang, 2012), Y liangyou 957 (high-temperature tolerant), Tianyouhuazhan (more sensitive at high temperature than Huanghuazhan) (Duan et al., 2012), Taiyou390 (indica-type three-line hybrid rice), Y liangyou 1 (indica type two-line hybrid rice), and Zhongzao 39 (inbred indica rice), and were respectively numbered 18Q001, 18Q002, 18Q003, 18Q004, 18Q005, 18Q006. These six varieties were provided by Hunan Hybrid Rice Research Centre and the characteristics of their thermosensitive reaction were obtained according to the variety registration information and related articles. The rice materials were sown in three batches at the experimental field of the Hunan Hybrid Rice Research Center in Changsha City, Hunan Province, in 2018. These three batches of rice materials were sowed on May 21, May 31, and June 10, sequentially. Accordingly, the transplanting data were obtained on June 10, June 21, and June 30. Three hundred plants were sown for each variety, and the field sowing, transplanting, and management methods were the same for all varieties of the three batches of rice. The corresponding numbers of the six rice varieties in three batches were shown at Supplementary Table 1. Two automatic temperature and humidity recorders (HOBO, Onset Computer Corp, Bourne, MA, USA) were installed 100 cm above the soil in the field to measure the real-time temperature.

After physiological maturation, 100 panicles were randomly selected for the same rice variety of the same sowing batch and were immediately placed in a 35 °C oven to dry until the moisture of every grain reached 14% (Zhu et al., 2019). All rice panicles were then threshed, dehulled, milled, and polished. The polished rice was analyzed for appearance and milling qualities. Starch extracted from the polished rice was used to measure a series of starch-related physiological and biochemical indexes: amylose content, starch granule morphology, crystal structure, water solubility index, swelling power, thermal characteristics, pasting property, starch granule size distribution, and so forth.

2.2. Starch isolation

Starch was extracted using the alkaline steeping method described by Takeda, Takeda, Mizukami, and Hanashiro (1999) with minor modifications. In brief, the dried polished rice sample was immersed in a 0.14% sodium bisulfate solution at room temperature for 24 h. The steeped grain sample was mixed with enough 0.14% sodium bisulfate solution and ground into a slurry. The milled slurry was filtered through a 200-mesh sieve and then centrifuged at 3000 rpm for 20 min. The faint-colored supernatant was removed, while the remaining sediment was re-suspended in MilliQ water and centrifuged at 3000 rpm for 20 min; this process was repeated five times. The isolated starch was placed in an oven at 55 °C to dry rapidly, and then the dried starch was ground to pass through a 200-mesh sieve and kept in a dryer.

2.3. Determination of the apparent amylose content (AAC)

The AAC was measured by using the iodine reagent colorimetric method reported by Man et al. (2012). The absorbance value was measured at 720 nm, and AAC was calculated by means of a standard curve, which was obtained by using potato amylose and corn amylopectin as standard samples.

2.4. Observation of starch granule morphology and size analysis

Starch granule morphology was observed by scanning electron microscopy (SEM; Philips XL-3, The Netherlands) (Kong et al., 2015). The starch granule size distribution was measured using a Malvern laser particle size analyzer (Mastersizer 3000; Malvern Panalytical, England). Starch powder (100 mg) was weighed and dispersed in 1 mL of absolute ethanol, which was then stirred at 2000 rpm. The blended samples were placed in the Mastersizer 3000 for determination. The results were analyzed using Mastersizer 3000 software (Blazek & Copeland, 2008).

2.5. X-ray diffraction (XRD) measurement

The XRD analysis of starch was performed on an X-ray diffractometer (D8 Advance; Bruker-AXS, Karlsruhe, Germany). The starch samples were scanned in the 2θ range of 3–35° at a rate of 1°/min and a step size of 0.02°. The results and the relative crystallinity (%) calculations were obtained by MDI Jade 6.0 software.

2.6. Thermal characteristics analysis

The thermal properties of starch were measured using a differential

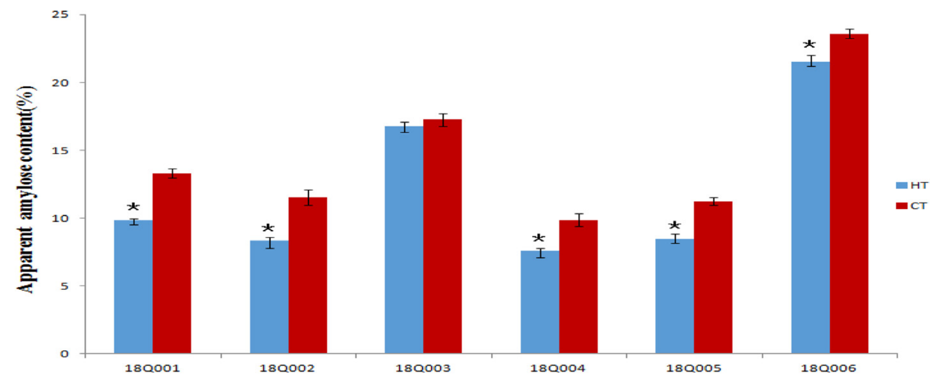

Fig. 1. Apparent amylose content of the first and third sowing date batch of every variety under HT and CT treatment during the grain filling stage. Level of significance is expressed as * for $P < 0.05$ between temperature treatments.

Table 1
Effects of high temperature on thermal properties of rice starches at the grain filling stage.

NO.	T_o (°C)	T_c (°C)	T_p (°C)	ΔH(J/g)
18Q001-1	69.36 ± 0.06a	77.89 ± 0.09a	73.57 ± 0.13a	11.05 ± 0.12a
18Q001-3	65.15 ± 0.08b	75.53 ± 0.11b	69.90 ± 0.12b	10.71 ± 0.11b
18Q002-1	75.14 ± 0.28a	83.78 ± 0.12a	79.95 ± 0.12a	6.69 ± 0.24a
18Q002-3	72.16 ± 0.16b	82.16 ± 0.34b	77.72 ± 0.15b	5.46 ± 0.39b
18Q003-1	73.58 ± 0.13a	83.42 ± 0.30a	78.91 ± 0.47a	12.16 ± 0.43a
18Q003-3	72.04 ± 0.15b	81.80 ± 0.16b	76.76 ± 0.20b	12.35 ± 0.12a
18Q004-1	67.96 ± 0.28a	84.65 ± 0.08a	79.56 ± 0.15a	13.14 ± 0.07a
18Q004-3	66.68 ± 0.12b	84.18 ± 0.13b	78.02 ± 0.19b	12.57 ± 0.12b
18Q005-1	66.57 ± 0.24a	76.27 ± 0.17a	71.79 ± 0.15a	11.72 ± 0.24a
18Q005-3	65.36 ± 0.19b	75.32 ± 0.17b	70.49 ± 0.16b	11.32 ± 0.14b
18Q006-1	73.91 ± 0.34a	81.53 ± 0.25a	77.66 ± 0.14a	11.11 ± 0.24a
18Q006-3	73.21 ± 0.21a	81.07 ± 0.19a	77.61 ± 0.11a	11.00 ± 0.34a

Data are shown as the mean ± standard error of triplicate measurements. Different letters are followed after standard deviation to express significantly different ($p < 0.05$).

scanning calorimeter (Model Q2000; TA Instruments Ltd., USA). A 10 mg starch sample was weighed and dispersed in 30 μL of sterile water, and then the suspension was sealed in an aluminum oxide pan at a room temperature for 24 h. The mixture was placed in a differential scanning calorimeter and heated at a rate of 10 °C/min. The temperature was increased from 30 °C to 95 °C, and the heat change data were collected for analysis using Universal Analysis software (Zhu et al., 2019).

2.7. Pasting property measurement

The pasting properties of starch were analyzed by using a Rapid Visco-Analyzer (RVA) (Model RVA Super 4; Newport Scientific, Australia). The test profile was analyzed according to the method described by Blazek and Copeland (2008) with minor modifications.

2.8. Water solubility index and swelling power assay

Water solubility index and swelling power were determined using the method reported by Konik-Rose et al. (2001), Kong, Bao, and Corke (2009). In brief, 100 mg of starch powder was weighed directly into a test tube, and then 10 mL of MilliQ water was added. The suspension was vortexed completely and incubated in a 95 °C water bath for 30 min with frequent mixing (at 5 min intervals). The tube was then cooled to room temperature and centrifuged at 3000*g* for 20 min. The supernatant was removed and the lower colloid remaining was weighed (W_s). The top supernatant was dried in a forced-air oven at 100 °C until constant weight (W_1) was reached. The swelling power (SP) and water solubility index (WSI) were calculated as follows:

$$WSI = W_1/0.1 \times 100;\quad SP = W_s/[0.1 \times (100\% - WSI/100)]\ (g/g)$$

2.9. Statistical analysis

All parameters shown in the tables and figures used in this article represent the mean values of the experimental data obtained from triplicate tests for all varieties sown during the three planting periods. The analysis of all data was performed using the SPSS16.0 Statistical Software Program. Two-way analysis of variance and Tukey's tests were used to determine whether statistically significant differences ($P < 0.05$) existed between the means.

3. Results and discussion

3.1. Changes in temperature from the three sowing dates

The optimal-growth temperature for rice is 22–27 °C in the grain-filling stage according to previous research (Deng et al., 2015; Wakamatsu et al., 2007). In this study, the mean daily temperature of 40 days after the initial heading stage for all varieties was calculated from the three sowing batches, which were divided into 22–27 °C for the control temperature (CT) and higher than 27 °C for high temperature (HT). Hence, except for 18Q006, the other varieties from the first sowing date were subjected to HT treatment during the grain-filling stage, while the third was subjected to CT treatment. For 18Q006, temperature during the grain-filling stages for the first and third batches were considered as HT. Overall, the daily mean temperature during the grain-filling stage of all varieties in the first sowing batch was higher than the corresponding third sowing batch (Supplementary Fig. 1). Hence, all varieties from the first sowing batch exposed to HT and the corresponding ones from the third sowing batch grown at CT were analyzed in this study. For the second sowing batch, all of them were subjected to HT except 18Q002-2 being considered as CT, and the temperature difference between the second and third sowing batches was less than that between the first and third, which was not conducive to the analysis of the changes in the physical and chemical properties of rice starches (Supplementary Table 1).

3.2. Rice processing and appearance quality

The polished-rice rate (%) and head rice rate (%) were used as the main indexes to evaluate grain-processing quality, and the appearance quality was mainly evaluated by the degree of chalkiness (%). Except for 18Q002 and 18Q006, a significant decrease ($P < 0.05$) in polished-rice rate was found between CT and HT for the same variety at the grain-filling stage (Supplementary Table 2). 18Q002 was not be affected by HT, which might be the result of the HT-tolerant character of Y Liangyou 957. Meanwhile, 18Q006-1 and 18Q006-3 were both under

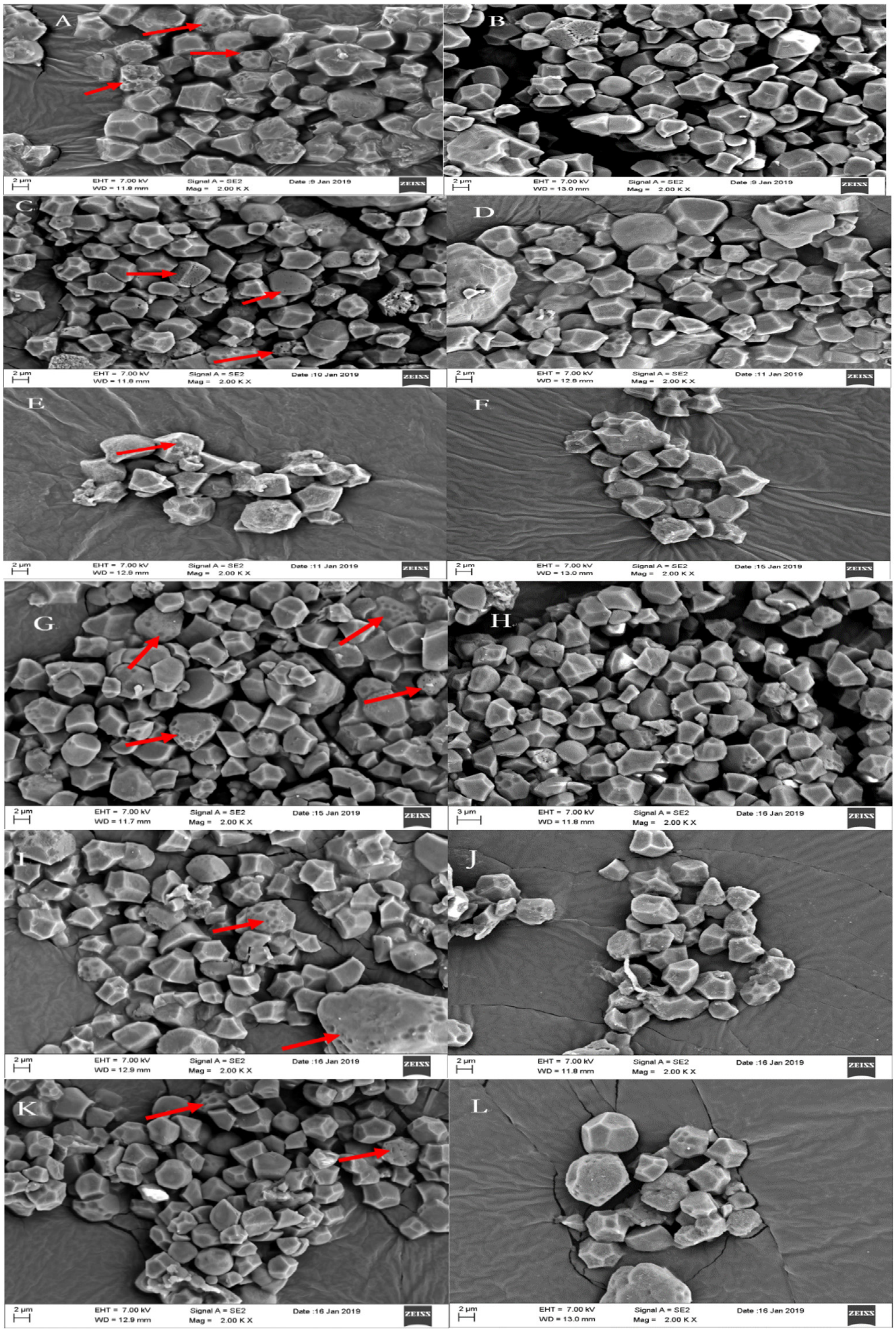

Fig. 2. Scanning electron photomicrographs of rice starch from HT and CT. A, C, E, G, I, K were respectively the starches from 18Q001, 18Q002, 18Q003, 18Q004, 18Q005, 18Q006 ripen at HT during the filling stage; B, D, F, H, J, L were respectively the starches from 18Q001, 18Q002, 18Q003, 18Q004, 18Q005, 18Q006 grown at CT during the filling stage.

HTs with minor differences (only 1.3 °C), which might be the main reason for the absence of a significant difference in polished-rice rate. Head-milled rice rate (%) decreased significantly for the other varieties except 18Q006. There was no significant difference among varieties in the ratio of grain length to width between HT and CT, implying that HT had a minor effect on length to width ratio. Chalkiness degree increased significantly for all other varieties except 18Q001 and 18Q002, implying that 18Q001 and 18002 had better HT tolerance. Previous research indicated that an increase in chalkiness was mainly attributable to a reduction of assimilate supply and an increase in grain-filling rate (Liu et al., 2013).

Therefore, HT at the grain-filling stage can significantly decrease the polished-rice rate (%) and the head-milled rice rate (%) and increase chalkiness, resulting in poor processing and appearance quality, which was in accordance with previous studies (Ambardekar, Siebenmorgen, Counce, Lanning, & Mauromoustakos, 2011; Lanning,

Table 2
Effects of high temperature on diameter of rice starch granule.

NO.	D [3, 2]	D [4, 3]
18Q001-1	6.478 ± 0.057b	8.450 ± 0.133b
18Q001-3	7.118 ± 0.012a	9.921 ± 0.013a
18Q002-1	6.136 ± 0.025b	9.412 ± 0.002b
18Q002-3	7.369 ± 0.077a	9.519 ± 0.008a
18Q003-1	6.460 ± 0.023b	8.414 ± 0.034b
18Q003-3	6.896 ± 0.019a	9.207 ± 0.001a
18Q004-1	5.928 ± 0.023b	7.921 ± 0.003b
18Q004-3	6.242 ± 0.019a	8.097 ± 0.088a
18Q005-1	6.235 ± 0.022a	8.702 ± 0.008a
18Q005-3	6.308 ± 0.040a	8.705 ± 0.006a
18Q006-1	6.391 ± 0.002b	8.501 ± 0.008b
18Q006-3	7.399 ± 0.030a	9.970 ± 0.034a

Data is shown as the mean ± standard error of triplicate measurements. Different letters are followed after standard deviation to express significantly different ($p < 0.05$).

Siebenmorgen, Counce, Ambardekar, & Mauromoustakos, 2011). However, these characteristics were affected by different varieties. For example, 18Q002, which was more resistant to high temperatures, did not have a significant difference in polished-rice rate and degree of chalkiness.

3.3. Apparent amylose content

Except for 18Q003, the apparent amylose content of the other five rice varieties significantly decreased in response to HT stress in the grain-filling stage (Fig. 1), which was similar with previous studies (Lin et al., 2010; Liu et al., 2013). Jiang, Dian, and Wu (2003) hypothesized that the reduction of the apparent amylose content might be due to the reduced activity of granule-bound starch synthase in grains that had been exposed to HT in the filling stage.

However, results for the effect of HT on the amylose content were controversial, with three different main viewpoints. Amylose content showed a decrease under high temperature during the grain-filling stage in our studies. These inconsistent results may be attributed to the different experimental materials chosen by the different studies.

3.4. Thermal properties of rice starches

The thermal properties of rice starches have been shown to be closely associated with milled-rice ECQ (Zhang et al., 2016; Fitzgerald, McCouch, & Hall, 2009). The thermal properties of rice starches are usually explained by the GT (onset, T_o; peak, T_p; conclusion, T_c) and gelatinization enthalpy (ΔH). In our studies, rice starches had significantly and consistently higher gelatinization temperature, viz., T_o, T_p, and T_c, at high temperature, except for 18Q006 (Table 1). The gelatinization temperature reflected the cooking difficulty of rice, resulting in higher cooking temperature and longer cooking time required for milled rice matured at high temperature (Zhang et al., 2016). In addition, rice varieties had a significant increase in ΔH, except for 18Q003 and 18Q006. Kong et al. (2015) reported that the gelatinization enthalpy was negatively correlated with the apparent amylose content. So the increase of the gelatinization enthalpy could be attributed to the decrease in AAC in response to HT stress. However, 18Q003 showed no significant difference in gelatinization enthalpy, which was consistent with the response to AAC at high temperature. 18Q006 also did not have a significant difference in GT and gelatinization enthalpy, which may be due to the minor temperature difference between 18Q006-1 and 18Q006-3. Gelatinization enthalpy reflected the degree of starch crystallization, a higher enthalpy implied that more energy was necessary to melt starch crystals, resulting to the polished rice being more difficult to cook. Our results showed that high temperature increased the gelatinization temperatures and gelatinization enthalpy of rice starch, resulting in greater difficulty in gelatinization of milled rice, which might be one of the most important factors affecting the cooking quality of rice.

3.5. Starch granule morphology and granule size distribution

The results of starch granule morphology obtained by SEM showed that starch granules of all varieties (HT and CT for the first and the third sowing batches) were polygonal, with several sharp angles (Fig. 2), which were similar to previous studies (Zhang et al., 2016; Mir & Bosco, 2014). However, some differences were found between rice starch granules obtained under HT and CT. The major difference was that HT starch granules were pitted and had an uneven surface, while starch granules under CT had a smooth surface. Similarly, Zhu et al. (2019) reported that rice starch granule surfaces that underwent field preharvest sprouting were more pitted and rougher than those of normal starch granules. Li et al. (2015) showed that high temperature at the grain-filling stage could enhance α-amylase activity, resulting in pitted and uneven starch granule surfaces.

As shown in Table 2, D [3, 2] (surface area mean diameter) and D [4, 3] (volume mean diameter) of the rice stressed by high temperature significantly decreased except for 18Q005. Similarly, Tashiro and Wardlaw (1991) indicated that a temperature higher than 26 °C at the filling stage led to smaller average diameter of japonica starch particles. The decrease of starch mean granule size might be due to the higher activity of α-amylase (Li, Zhang, Fu, Li, & Li, 2017). For 18Q005, there was no significant difference for D [3, 2] and D [4, 3] in response to HT stress, which implied that the magnitude of this effect was cultivar dependent. This might be attributed to the different effects of high temperature on large, medium and small granule starches, which was similar to the report in wheat (Yan et al., 2008).

Table 3
Effects of high temperature on pasting properties of rice starch at grain filling stage.

NO.	PV	TV	CPV	SB	BK
18Q001-1	742.67 ± 5.03a	570.33 ± 5.51b	1009.33 ± 3.51b	439.33 ± 3.51b	172.67 ± 5.03a
18Q001-3	710.33 ± 4.51b	621.00 ± 4.36a	1518.00 ± 6.00a	900.67 ± 4.04a	89.33 ± 3.06b
18Q002-1	806.33 ± 3.79a	525.00 ± 4.58b	883.00 ± 6.08b	353.00 ± 4.58b	282.00 ± 4.00a
18Q002-3	733.67 ± 3.51b	555.33 ± 5.86a	1090.00 ± 9.00a	537.67 ± 3.06a	180.33 ± 4.04b
18Q003-1	837.00 ± 4.00a	712.00 ± 6.24a	1190.00 ± 8.00b	481.00 ± 5.57b	129.00 ± 6.24b
18Q003-3	727.67 ± 4.16b	532.33 ± 4.51b	1313.33 ± 6.11a	781.67 ± 3.79a	199.33 ± 5.86a
18Q004-1	799.00 ± 3.00b	467.33 ± 5.69b	873.00 ± 3.61b	405.00 ± 4.00a	331.00 ± 3.61a
18Q004-3	828.67 ± 2.08a	525.00 ± 5.57a	883.33 ± 4.62a	406.33 ± 7.64a	303.00 ± 4.58b
18Q005-1	950.00 ± 2.00b	554.67 ± 5.51b	912.00 ± 3.61b	357.67 ± 4.51b	395.67 ± 5.03a
18Q005-3	969.67 ± 2.52a	636.00 ± 4.58a	1072.00 ± 5.29a	434.33 ± 3.06a	336.67 ± 4.51b
18Q006-1	729.67 ± 2.08b	655.00 ± 6.56b	1574.67 ± 5.86b	920.67 ± 2.52a	73.33 ± 2.52b
18Q006-3	1017.67 ± 3.06a	858.33 ± 4.51a	1656.67 ± 4.73a	795.33 ± 4.73b	158.67 ± 2.52a

Data are shown as the mean ± standard error of triplicate measurements. Different letters are followed after standard deviation to express significantly different ($p < 0.05$).

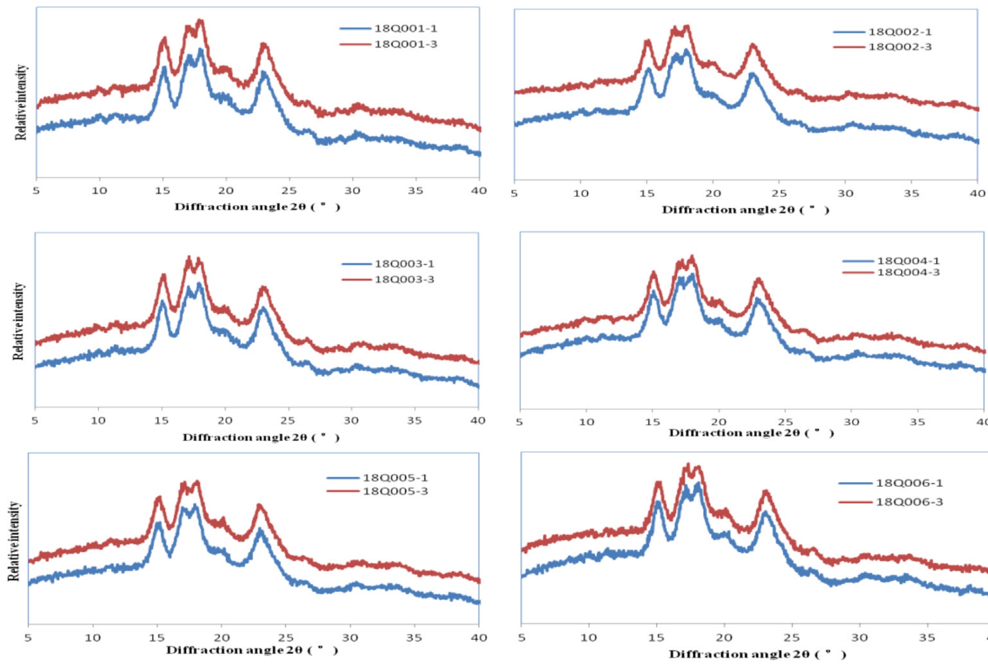

Fig. 3. Effects of high temperature and optimal temperature on the X-ray diffraction patterns of rice starch.

3.6. Starch pasting properties as determined by RVA analysis

The pasting properties of starch are closely related to the ECQ of milled rice. The pasting profiles of rice starch were analyzed by RVA. Their relevant pasting property parameters were shown in Table 3. Peak viscosity (PV) variation between HT and CT were not consistent among the varieties. High temperature increased PV significantly for 18Q001, 18Q002, and 18Q003, while it decreased obviously for the other varieties. This indicated that the effect of high temperature on PV was correlated with the rice cultivar. The trough viscosities (TVs) were lower under HT, except 18Q003, which had a higher TV. The cool-paste viscosity (CPV) was lower for all varieties exposed at HT than those grown at CT. Meanwhile, high temperature significantly reduced the setback (SB) values except for 18Q004, which showed no significant difference, and 18Q006, which had higher SB; the breakdown (BK) values increased significantly at high temperature except for 18Q003 and 18Q006. In terms of TV, SB, and BK, 18Q003 or 18Q006 had inconsistent variation compared with the other varieties. This may be attributed to the high amylose content of these two varieties, according to previous studies showing that pasting properties of starch were dependent on amylose content (Jane et al., 1999; Chun, Lee, Hamaker, & Janaswamy, 2015).

3.7. Starch crystal structure

All tested starches showed similar XRD patterns (Fig. 3), exhibiting A-type crystals with two strong 2θ peaks at approximately 15° and 23° and an unresolved double 2θ peak at 17° and 18°, which implied no change in crystal type between rice starches ripened at HT and those grown at CT. Further studies found that some changes in relative crystallinity of existing varieties at high temperature at the grain-filling stage were inconsistent, displaying an obvious increase for 18Q001 and 18Q005, as well as a significant decrease for the other cultivars (Supplementary Table 3). The changes in relative crystallinity may be associated with amylose content as well as amylopectin chain length distribution and the degree of polymerization (Zhu et al., 2019). Meanwhile, the head-milled rice rate may also be one of the influencing factors of inconsistent changes in relative crystallinity (Wei et al., 2011).

3.8. Water solubility index and swelling power

The swelling power and water solubility of the starches under HT and CT were shown as Supplementary Table 3. Except for 18Q006, the other varieties had higher significantly swelling power and water solubility, which might be associated with the lower amylose content under high temperature at the grain-filling stage. A previous study reported that amylose content could inhibit starch swelling and maintain the structural integrity of starch granules (Wei et al., 2011). Hence, lower amylose content under HT may help increase the water solubility index and swelling power. While there was no significant change existed in18Q006 for the water solubility index and swelling power, which might be attributed to the minor temperature difference between 18Q006-1 and 18Q006-3.

4. Conclusions

High temperature during the grain-filling period seriously affects the morphological structure and physicochemical properties of rice starch. Our results showed that high temperature during the grain-filling stage could negatively affect rice milling and appearance quality, but influence degree was cultivar-dependent. In addition, high filling temperature led to lower amylose content, as well as higher gelatinization properties, namely, gelatinization temperature and enthalpy, swelling power, and water solubility index. Meanwhile, the resulting pasting properties were slightly better, with lower setback, lower trough viscosities, and higher breakdown. The changes in the rice starch crystal type were not observed, but the variation of the relative crystallinity, as well as pitting and unevenness on the surface of the starch granules with lower granule size between HT and CT were observed. The results of this study provide a useful reference that will help breeders produce more high-temperature-tolerant rice varieties that adapt to changes in the environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2019.125817.

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