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Effects of experimental warming on physicochemical properties of *indica* rice starch in a double rice cropping system

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ABSTRACT

To evaluate the actual response of rice starch physicochemical properties to climate warming, a field warming experiment was conducted with four *indica* rice cultivars using free-air temperature increase (FATI) facility in a double rice cropping system. FATI facility increased rice canopy temperature by 1.4–2.1 °C during the entire growth period. The responses of starch physicochemical properties to experimental warming were basically consistent for both early and late rice. On average, experimental warming increased the starch relative crystallinity, granule average diameter, and amylopectin average chain length by 14.3%, 6.9%, and 2.4%, respectively. These resulted in starch with lower swelling power, water solubility, and pasting viscosity, but higher gelatinization temperatures and gelatinization enthalpy. Our study indicated that experimental warming affected the rice starch physicochemical properties, and would provide some useful information on how to guide the rice starch end use in food and non-food industries under climate warming.

1. Introduction

As one of the most important food crops in the world, rice (*Oryza Sativa* L.) feeds nearly half of the world's population (FAO, 2018). Starch comprising amylose and amylopectin molecules is the major component in rice, which accounts for approximately 90% of its total weight (Tester, Karkalas, & Qi, 2004; Chun, Lee, Hamaker, & Janaswamy, 2015). Rice starch physicochemical properties, such as granule size distribution, amylose content, amylopectin chain length distribution, relative crystallinity, thermal properties, and pasting temperature play an important role in rice quality (Chung, Liu, Lee, & Wei, 2011; Zhu, Wei et al., 2017; Dou et al., 2018), and also are used to evaluate cooked rice quality and starch-based food's mouthfeel (Ratnayake & Jackson, 2007; Li, Prakash, Nicholson, Fitzgerald, & Gilbert, 2016). Furthermore, rice starch as a common raw material has many advantages (e.g., pure white in color, smaller granules, non-allergic tasteless, and greater acid resistance) over other starches, which is widely used in either food or non-food industries (Wani et al., 2012).

Compared the period from 1850 to 1900, global mean surface temperature for the decades 2006–2015 has increased 0.85 °C, and it is likely to increase 1.5 °C between 2030 and 2052 (IPCC, 2018). The increasing global mean surface temperature will have serious implications on rice crop production, food security, and human survival (Rehmani et al., 2014; Cai et al., 2016). Many studies have investigated that higher temperature or elevated temperature could deteriorate rice milling, appearance and cooked quality, and also change its eating quality in the past years (Jing et al., 2016; Xiong, Ling, Huang, & Peng, 2017). Meanwhile, the rice starch physicochemical properties are highly affected by the air temperature during rice growth period (Patindol, Siebenmorgen, & Wang, 2015). There are few researches have studied the changes of rice starch physicochemical properties under higher temperature. Liu et al. (2017) reported that high temperature during grain filling period increased the rice starch granules average diameter, and it was mainly attributed to enhance the proportion of large starch granules. Dou et al. (2018) found that the number of short amylopectin chains could be reduced in the rice starch, whereas the number of intermediate amylopectin chains could be increased under field warming condition during grain-filling stage. These changes of starch fine structure under higher growth temperature might result in higher gelatinization temperature, gelatinization enthalpy, and pasting viscosities, but lower setback of rice flour, consequently deteriorative rice cooking quality and cooked rice palatability in sensory

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tests, which was unacceptable for the consumers (Chun et al., 2015; Zhang et al., 2016). However, the previous studies about the effects of high temperature on rice starch physicochemical properties were performed under the controlled conditions (e.g., greenhouse) or with *japonica* rice cultivars. Therefore, the further studies should be conducted to reveal the effects of global warming on *indica* rice starch physicochemical properties under field condition, systematically.

China is the largest country of rice grain production and consumption in the world with a planting area of 30.7 million ha and grain yield of 212.7 million tons (NBSC, 2018). In 2018, *indica* rice planting area and grain yield account for about 66% and 63% of China rice production, respectively (CNRRI, 2019). *Indica* rice is one of the most staple food for Chinese, especially in Southern China. In addition, *indica* rice, especially early season *indica* rice is widely used to make rice noodles due to the high amylose content. As one of the most important rice-based cropping systems in China, the double rice cropping system accounts for nearly 34.9% of rice planting area and 29.7% grain yield (NBSC, 2018). It not only can enhance food security, but also contribute to improving the rice planting structure and satisfying the people's diet habit for different rice types in Southern China. Our previous studies had reported that experimental warming could improve the milling quality, but decrease the appearance quality of *indica* rice grain in the double rice cropping system in Southern China (Yang et al., 2018). However, little is known about the effects of experimental warming during rice growth period on starch physicochemical properties of *indica* rice grain in the double rice cropping system. In this study, we conducted a field experiment with the free-air temperature increase (FATI) facility and four *indica* rice cultivars to study the actual and comprehensive response of rice starch structural and physicochemical properties to climate warming.

2. Materials and methods

2.1. Site descriptions

The experiment was conducted in Shanggao Experimental Station (115°09′E, 28°31′N) of Jiangxi Agricultural University in 2018. The experimental site was located within the major double-cropped rice production region in Jiangxi, China. The double rice cropping system consists of early rice and late rice followed by winter fallow. The early season rice is planted from March to July, and the late season rice from June to November. The area has a subtropical monsoon climate with a mean annual temperature of 17.5 °C and mean annual precipitation of 1650 mm. The properties of topsoil (0–15 cm) before the experiment in 2018 were: soil pH 5.5, organic carbon 20.5 g kg^{-1}, total nitrogen 2.0 g kg^{-1}, alkaline hydrolyzable nitrogen 190.0 mg kg^{-1}, available phosphorus 20.0 mg kg^{-1}, available potassium 65.1 mg kg^{-1}.

2.2. Experimental design

There were two treatments (i.e., warming and ambient temperature) with three replicates in a randomized complete block design. Each plot was 5 m × 10 m with width and length in size. The FATI system was established according to Dou et al. (2018). Briefly, one infrared heater (1500 W, 180 cm in length, 20 cm in width) was suspended 75 cm above rice canopy in each warming plot for a cultivar (Fig. S1a). A'dummy' heater with the same size was suspended to imitate the shading effects of the heater. Each infrared heater formed a 1.8 m × 1.5 m sampling area with uniform and reliable warming effects (Fig. S1b and c).

The warming treatments started immediately following transplanting and ended at maturity. Rice canopy temperature was monitored continuously with an interval of 1 h in each plot by a digital temperature monitor (ZDR-41, Hangzhou Zeda Electronic Instrument, Zhejiang, China). This FATI facility caused significant increase in the daily mean temperature by 1.4–2.1 °C during the entire growth period, 1.4–1.9 °C during the pre-heading period, and 1.4–2.3 °C during the post-heading period (Table 1).

Table 1
Rice canopy average temperature (°C) of difference growth period under FATI facility.

Seasons	Cultivars	Treatments	Pre-heading	Post-heading	Entire growth period
Early rice	XZX	Ambient	24.9	27.8	26.1
		Warming	26.4	29.3	27.7
	QLY	Ambient	24.9	28.2	26.3
		Warming	26.3	29.6	27.7
Late rice	JXN	Ambient	30.1	21.0	25.8
		Warming	32.0	23.3	27.9
	TY	Ambient	30.9	25.4	28.1
		Warming	32.6	27.3	30.2

2.3. Crop management

The tested early rice cultivars were Xiangzaoxian45 (XZX, inbred *indica* rice) and Qiliangyou2012 (QLY, hybrid *indica* rice); the late rice cultivars were Jiuxiangnian (JXN, inbred *indica* rice) and Taiyou398 (TY, hybrid *indica* rice). The sowing, transplanting, heading, and maturity dates were showed in Table S1. Seedings were transplanted manually at a hill space of 20 cm × 13 cm in early rice season and 25 cm × 13 cm in late rice season with three seedlings per hill. Urea, calcium magnesium phosphate, and potassium chloride were used for nitrogen, phosphorus, and potassium fertilizers, respectively. The application of nitrogen, phosphorus, and potassium fertilizers were 165.0, 35.9, and 123.3 kg ha^{-1} in early rice season, and were 210.0, 46.5, and 156.2 kg ha^{-1} in late rice season, respectively. Nitrogen fertilizer were split-applied: 50% at basal, 20% at early tillering, and 30% at panicle initiation in the early rice season, and 40% at basal, 20% at early tillering, and 40% at panicle initiation in the late rice season. All phosphorus fertilizer was applied at basal, and 70% potassium was applied at basal with the remainder at panicle initiation for both early and late rice, respectively. The field was kept flooded from transplanting until mid-season drainage, and then was intermittently irrigated until maturity. Other field management measures (e.g., diseases, weeds, and insects) were the same as regular double cropping rice production. At maturity, 50 plants in each plot were harvested for the determination on starch structural and physicochemical properties.

2.4. Measurements

Prior to starch physicochemical properties determination, rice grains were air-dried and stored at room temperature for 3 months, then were milled using a rice polisher (LTJM-5588, Taizhou Grain Instrument, Zhejiang, China). The milled rice was ground into powder using a cyclone sample mill (JXFM110, Hangzhou Dacai Photoelectric Technology Limited Company, Zhejiang, China) and passed through a 100-mesh sieve.

2.4.1. Starch isolation

According to the method of Wei et al. (2010), rice starch was isolated with the following steps: Firstly, rice flour samples (25 g) were dispersed in 30 ml of 0.45% sodium metabisulfite aqueous solution with 10 mg g^{-1} alkaline protease at 42 °C overnight to remove protein. Then the starch slurry was ground in mortar with pestle and sieved (200 mesh), the filtrate was centrifuged (8000 g, 10 min) and the supernatant was discarded, and the starch pellet was washed with 30 ml of ultrapure water, and centrifuged (8000 g, 10 min), and the supernatant was discarded again. The wash and centrifugal steps were repeated three times. Finally, the starch was air-dried and sieved (200 mesh). The amylose was determined according to the national standard for rice

Table 2
Effects of experimental warming on amylopectin chain length distribution.[a]

Seasons	Cultivars	Treatments	Average chain length	Amylopectin chain length distribution (%)			
				DP ≤ 12	DP13-24	DP25-36	DP ≥ 37
Early rice	XZX	Ambient	20.5b	26.9a	48.4a	12.5a	12.3b
		Warming	21.0a	26.8a	47.3b	12.6a	13.3a
	QLY	Ambient	20.9a	27.9a	46.5a	12.4a	13.2a
		Warming	20.9a	28.4a	45.9a	12.5a	13.2a
Late rice	JXN	Ambient	20.7b	27.9a	46.4a	12.8b	12.8b
		Warming	21.3a	27.6a	45.0b	13.2a	14.2a
	TY	Ambient	20.8b	26.5a	45.7a	13.0b	14.8b
		Warming	21.7a	27.0a	44.5b	13.2a	15.3a

[a] Different letters indicate significant difference at $P < 0.05$ in the same cultivar.

quality evaluation 'GB/T 17891-2017', the People's Republic of China (NBQTC, 2017).

2.4.2. Amylopectin chain length distribution

Amylopectin chain length distribution was analyzed by high-performance anion-exchange chromatography (HPAECICS-5000, Thermo Fisher Scientific, Sunnyvale, America) equipped with a pulsed-amperometric detector according to the research of Zhang et al. (2016).

2.4.3. Starch granule average diameter

Starch granule size distribution was measured with a laser particle size analyzer (Mastersizer 3000, Malvern, England). The starch sample (50 mg) was suspended with 10 ml ultrapure water in the dispersion tank of the instrument. The instrument was adjusted to measure starch granule size ranging from 0.1 to 2000 μm. Starch granule average diameter was calculated from instrument software.

2.4.4. X-ray diffraction analysis

The X-ray diffraction patterns of rice starch were determined by an X-ray powder diffractometer (X'Pert Pro, PANalytical, Netherlands). The starch sample was operated at 200 mA and 40 kV, and the diffraction angle was 2θ, ranged at 3–40° with a speed of 0.02° and a count time of 0.6 s. Relative crystallinity (%) was calculated by MDI Jade 6 software.

2.4.5. Swelling power and water solubility

Swelling power and solubility of rice starch were determined according to the method of Lu, Cai, Shi, Zhao, and Lu (2015) with slight modification. Starch samples (100 mg; m_0) mixed with 5 ml water was put in a 10 ml centrifuge tube (m_1) and cooked at 95 °C for 30 min. The sample was then cooled to room temperature and centrifuged at 8000 g for 10 min. The supernatant was discarded. The residue in the centrifuge tube was weighed (m_2), and then dried to constant weight (m_3) at 60 °C. The swelling power and water solubility were calculated as follows:

$$\text{Swelling power (g g}^{-1}) = \frac{m_2 - m_1}{m_3 - m_1}$$

$$\text{Water solubility (\%)} = \frac{m_0 + m_1 - m_3}{m_0} \times 100$$

2.4.6. Starch thermal properties

The thermal properties of rice starch were carried out by using a differential scanning calorimetry (DSC Q2000, TA Instruments, America) according to Zhu, Zhang et al. (2017) with some modifications. Starch samples (5 mg) was mixed with 10 ml ultrapure water and sealed in an aluminum pan at 4 °C overnight, and equilibrated for 1 h at room temperature before analyzed. The DSC analyzer was calibrated with an empty pan as reference first and then heated at the rate of 10 °C min^{-1} from 25 to 100 °C. The onset temperature (To), peak of gelatinization temperature (Tp), conclusion temperature (Tc), and gelatinization enthalpy (ΔH_{gel}) were recorded.

2.4.7. Starch pasting properties

The pasting properties of rice starch were evaluated using a rapid viscosity analyzer (RVA, Newport Scientific, Australia) according to the AACC method 61-02 (AACC, 1999). The peak viscosity (PV), trough viscosity (TV), final viscosity (FV), breakdown viscosity (BD = PV–TV), setback viscosity (SB = FV–TV), and pasting temperature (P_{temp}) were recorded.

2.5. Statistical analysis

For statistical analysis, data processing was analyzed with SPSS 20.0 statistical software program. The comparison between ambient and warming treatments for each cultivar was down by one-way ANOVA. Differences were determined to be statistically significant when $P < 0.05$.

3. Results and discussion

3.1. Amylopectin chain length distribution

In this study, experimental warming showed significant impacts on amylopectin average chain length and chain length distribution, except for QLY (Table 2). Experimental warming significantly increased amylopectin average chain length by 2.4% of XZX for early rice, 2.9% of JXN and 4.3% of TY for late rice. Amylopectin were classified into four types depending on the chain length: A (DP ≤ 12), B1 (13 ≤ DP ≤ 24), B2 (25 ≤ DP ≤ 36), and B3 (DP ≥ 37) (Hanashiro, Abe, & Hizukuri, 1996). There was no significant effect of experimental warming on the ratio chain A for both early and late rice. Experimental warming significantly decreased the ratio of chain B1 by 2.3%, but increased the ratio of chain B3 by 8.1% of XZX for early rice. For late rice, experimental warming decreased the ratio of chain B1 by 3.0% and 2.6%, whereas increased chain B2 by 3.1% and 1.5%, and chain B3 by 10.9% and 3.4% of JXN and TY, respectively. The response of amylopectin chain distribution to experimental warming was similar with previous studies (Chun et al., 2015; Dou et al., 2018). The synthesis of amylopectin is mainly regulated by soluble starch synthase (SSS) and starch branching enzyme (SBE) (Smith, Denyer, & Martin, 1997; Dou et al., 2018). High temperature has depressing effect on SBE or promoting effect on SSS (Liao et al., 2015; Timabud, Yin, Pongdontri, & Komatsu, 2016), and results in the reduction of the ratio of chain B1 and the increase of the ratio of chain B2 and B3 of amylopectin.

3.2. Amylose content, starch granule average diameter, and relative crystallinity

Amylose content of grain is an important factor for determining cooked rice hardness and taste (Zhong, Cheng, Wen, Sun, & Zhang,

Table 3
Effects of experimental warming on amylose content, starch granule average diameter, and relative crystallinity.[a]

Seasons	Cultivars	Treatments	Amylose content (%)	Average diameter (μm)	Relative crystallinity (%)
Early rice	XZX	Ambient	18.0a	4.1b	22.9b
		Warming	17.8a	4.5a	26.4a
	QLY	Ambient	15.9a	4.0b	27.1b
		Warming	15.2a	4.3a	33.3a
Late rice	JXN	Ambient	16.1a	3.7b	25.0a
		Warming	15.7a	3.9a	25.9a
	TY	Ambient	17.1a	4.2b	23.5b
		Warming	17.4a	4.4a	27.1a

[a] Different letters indicate significant difference at $P < 0.05$ in the same cultivar.

Table 4
Effects of experimental warming on thermal properties of rice starch.[a]

Seasons	Cultivars	Treatments	To (°C)[b]	Tp (°C)[b]	Tc (°C)[b]	ΔH_{gel} (J g^{-1})[b]
Early rice	XZX	Ambient	66.2a	71.6a	85.5b	10.1a
		Warming	67.1a	72.3a	86.6a	10.7a
	QLY	Ambient	66.4b	72.0a	77.6b	9.8b
		Warming	67.5a	72.8a	79.5a	10.5a
Late rice	JXN	Ambient	62.0a	68.2a	73.5a	10.1a
		Warming	62.6a	68.8a	74.0a	10.4a
	TY	Ambient	66.2a	71.0b	75.9b	10.7a
		Warming	66.6a	71.9a	77.2a	11.1a

[a] Different letters indicate significant difference at $P < 0.05$ in the same cultivar.
[b] To, onset temperature; Tp, peak of gelatinization temperature; Tc, conclusion temperature; ΔH_{gel}, gelatinization enthalpy.

2010; Kong, Zhu, Sui, & Bao, 2015). Elevating temperature decreased the amylose content (Zhang et al., 2016), and rice grain with lower amylose content usually has soft texture and good test (Liu et al., 2013). However, our result showed that amylose content was not affected by experimental warming in both early and late rice (Table 3). The effect of high temperature on amylose accumulation in grain is regulated by granule-bound starch synthase (GBSS) (Smith, Denyer, & Martin, 1995; Cao et al., 2015). In the present study, moderate warming (i.e., 1.4–2.1 °C) might not change the activities of GBSS for amylose synthesis. Therefore, further studies will be required to focus on the mechanisms of amylose synthesis under warming condition.

Compared with ambient temperature treatment, warming significantly increased starch granule average diameter by 9.8% of XZX and 7.5% of QLY for early rice, and 5.4% of JXN and 4.8% of TY for late rice (Table 3). The results were consistent with previous report (Liu et al., 2017). Experimental warming increased starch granule average diameter. The reasons might be the increased ratio of large starch granules (> 2.6 μm) by number, volume, and surface area, respectively (Liu et al., 2017).

Generally, natural starches can be classified into A-, B-, and C-types according to their XRD patterns (Zhu, Wei et al., 2017). The X-ray diffraction patterns of the starches from the four *indica* rice cultivars growing under warming and ambient temperature conditions showed a typical A-type crystallinity (Fig. S2), with strong diffraction peaks at approximately 15° and 23° 2θ and an unresolved doublet at around 17° and 18° 2θ. Significant impacts on the cultivars of experimental warming were observed in the relative crystallinity, except for JXN cultivar (Table 3). Experimental warming significantly increased the relative crystallinity by 15.3% of XZX and 22.9% of QLY for early rice, respectively, and 15.3% of TY for late rice, which was in accordance with the study of Zhang et al. (2016) and Chun et al. (2015). Amylopectin content especially the longer amylopectin branch chains and starch granule size especially the larger granules are generally considered to be responsible for higher starch crystallinity (Chung et al., 2011; Zeng, Li, Gao, & Ru, 2011). Therefore, in this study, the increases in amylopectin average chain length, the ratio of chain B2 and B3, and starch granule size might be the main reasons for the increase of relative crystallinity.

3.3. Swelling power and water solubility

Swelling power and water solubility are used as a measure of the extent of interactions between starch chains within the amorphous and crystalline (Singh, Singh, Isono, & Noda, 2010). Experimental warming changed the swelling power and water solubility of different rice cultivars (Fig. 1). For early rice, experimental warming significantly reduced the swelling power by 9.3% of XZX and 6.4% of QLY, and the water solubility was significantly reduced by 11.7% of XZX. For late rice, experimental warming significantly reduced the swelling power by 8.0% of TY, and water solubility was also reduced by 31.8% of JXN and 26.4% of TY. These results might be attributed to the increase of starch granule average diameter, because larger starch granule had smaller specific area, which suggested that the water affinity of starch granule would be decreased (Zhu, Wei et al., 2017). In addition, starch with higher average chain length and long chains of amylopectin could also decrease swelling power (Srichuwong, Sunarti, Mishima, Isono, & Hisamatsu, 2005).

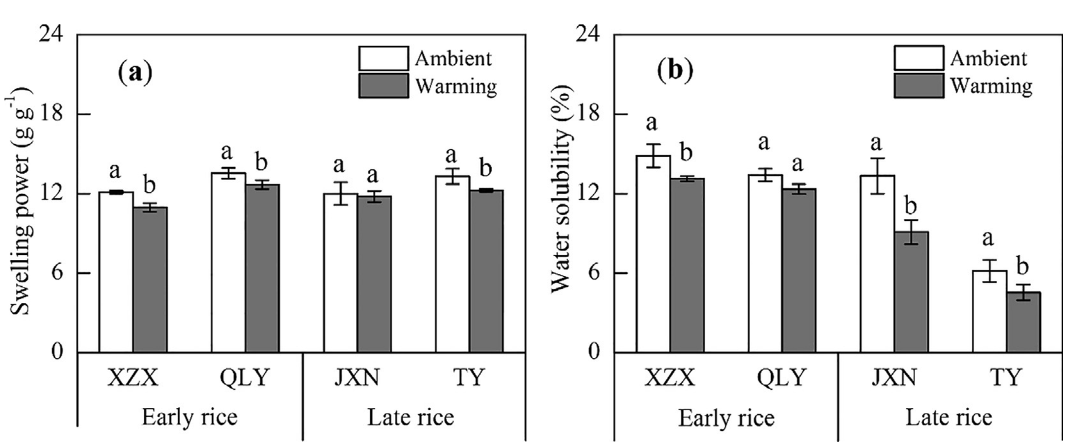

Fig. 1. Effects of experimental warming on swelling power (a) and water solubility (b) of rice starch. Different letters indicate significant difference at $P < 0.05$ in the same cultivar. Error bars represent SD ($n = 3$).

Table 5
Effects of experimental warming on pasting properties of rice starch.[a]

Seasons	Cultivars	Treatments	PV (cP)[b]	TV (cP)[b]	BD (cP)[b]	FV (cP)[b]	SB (cP)[b]	P_{temp} (°C)[b]
Early rice	XZX	Ambient	2775a	2064a	712a	3700a	925a	90.8a
		Warming	2515b	1786b	729a	3471b	956a	91.2a
	QLY	Ambient	2779a	1968a	811a	3546a	767a	86.2b
		Warming	2714a	1943a	771a	3477a	763a	87.8a
Late rice	JXN	Ambient	3097a	1747a	1350b	2968a	−130a	87.3b
		Warming	2868b	1389b	1479a	2656b	−212a	88.3a
	TY	Ambient	3347a	1585a	1762a	2445a	−902b	79.5a
		Warming	2956b	1392b	1564b	2289b	−667a	79.8a

[a] Different letters indicate significant difference at $P < 0.05$ in the same cultivar.
[b] PV, peak viscosity; TV, trough viscosity; BD, breakdown; FV, final viscosity; SB, setback; P_{temp}, pasting temperature.

3.4. Thermal properties of rice starch

The thermal properties of rice starch are closely related with the cooking quality (Chun et al., 2015). In this study, the gelatinization temperature (To, Tp, and Tc) and ΔH_{gel} showed increasing trend under warming temperature treatment (Table 4). Gelatinization enthalpy reflects the degree of starch crystallinity, it can be used to measure the changes of crystalline and double helical structures during starch gelatinization (Ji et al., 2004). Experimental warming only significantly increased the ΔH_{gel} by 7.1% of QLY for early rice, which might due to its higher relative crystallinity, as determined by the XRD spectra (Tang, Ando, Watanabe, Takeda, & Mitsunaga, 2000). For early rice, experimental warming significantly increased To by 1.1 °C of QLY, Tc by 1.1 °C of XZX and 1.9 °C of QLY. Tp and Tc were significantly increased by 0.9 °C and 1.3 °C of TY for late rice, respectively. The increase of rice starch gelatinization temperatures (To, Tp, and Tc) in the warming treatment was similar to the study of Zhang et al. (2016). Higher gelatinization temperatures mean higher cooking temperature and longer cooking time (Zhu et al., 2019). This suggested that the rice growing in warming treatment was hard to be well cooked, compared with ambient treatment. Moreover, higher gelatinization temperatures were related to higher relative crystallinity, more large-sized granules, and longer amylopectin chain length (Singh et al., 2010; Zhang et al., 2016; Dou et al., 2018; Zhu et al., 2019). The increasing trends of gelatinization temperatures could be confirmed through the data in Tables 2 and 3.

3.5. Pasting properties of rice starch

RVA is a useful tool to reflect the cooking and eating properties of cooked rice. Zhang et al. (2016) reported that rice grown under higher temperature showed a tendency to lower peak, trough, and final viscosity, and higher pasting temperature of rice starch, which showed the same phenomenon to our study (Table 5). Experimental warming significantly decreased the peak, trough, and final viscosity by 9.4%, 13.5%, and 6.2 of XZX for early rice, respectively. For late rice, experimental warming significantly decreased the peak viscosity by 7.4% and 11.7%, the trough viscosity by 20.5% and 12.2%, and final viscosity by 10.5% and 6.4% of JXN and TY, respectively. The pasting temperatures of QLY and JXN under warming treatment were significantly increased by 1.6 °C and 1.0 °C, respectively. Therefore, our results based on field experiments indicated that rice grown under warming condition might have lower cohesiveness and stickness, and higher hardness, resulting in higher cooking temperature and cooking time of rice starch. Pasting properties were affected by amylose content and amylopectin chain length distribution (Zhang et al., 2016). In the present study, warming lowered peak, trough, and final viscosity, which might due to the increase of amylopectin average chain length and the ratio of chain B2 and B3. Breakdown viscosity and setback viscosity were usually used to reflect the eating quality. In our results, the effects of warming on breakdown and setback viscosity varied among different cultivars. This might be related with the differences on rice genotypes. Therefore, further researches are required to study how physicochemical properties of rice starch influence the thermal and pasting properties in the future with warming condition.

4. Conclusions

Four *indica* rice cultivars were cultivated under warming and ambient temperature in a double rice cropping system in Southern China. The results of this study indicated that experimental warming could affect physicochemical properties (i.e., higher gelatinization temperature and enthalpy, lower pasting viscosity, swelling power, and water solubility). This might due to the changes of starch structure (i.e., larger starch granule average diameter, higher relative crystallinity, and longer amylopectin chain length). These experimental results provided some information that how to take breeding and agronomic managements to maintain rice or starch quality under climate warming.

CRediT authorship contribution statement

Taotao Yang: Investigation, Data curation, Writing - original draft. **Xueming Tan:** Investigation, Data curation, Writing - original draft. **Shan Huang:** Software, Methodology, Visualization. **Xiaohua Pan:** . **Qinghua Shi:** . **Yongjun Zeng:** Validation, Project administration. **Jun Zhang:** Validation, Project administration. **Yanhua Zeng:** Conceptualization.

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.2019.125981.

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