Research Article

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Response of yield and quality of *Japonica* rice to different gradients of moisture deficit at grain-filling stage in cold regions

https://doi.org/10.1515/chem-2024-0009
received February 3, 2024; accepted March 14, 2024

Abstract: Water stress significantly affects on rice yield and quality. Eight *Japonica* varieties from the first and second accumulated temperature zones of Heilongjiang Province were used as materials and four moisture gradients (0, −10, −25 and −40 kPa) were conducted at the grain-filling stage to clarify the effect of water stress on the rice yield and quality in cold regions. The results showed that the rice yield was reduced due to the decrease in the seed setting rate. Rice chalkiness was significantly increased by drought stress, especially under −10 kPa. The protein content of most varieties was significantly reduced and taste quality was increased under −25 to −40 kPa. The effect on protein components increased with increasing drought stress. The gel consistency decreased and the average chain length of amylopectin was less affected by drought. With an increase in moisture deficit, the rapid viscosity analyzer characteristics and chain length distribution of amylopectin showed a trend of first increasing and then decreasing or decreasing and then increasing. The response of starch to mild and severe drought varied. Our study provides a theoretical basis for the efficient utilization of water and high quality and yield of *Japonica* rice.

Keywords: *Japonica* rice, yield, quality, starch, moisture deficit

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1 Introduction

Global climate change and water scarcity threaten global food security, and the situation is expected to worsen as the global population grows [1]. Drought frequency and the area of global agriculture will increase by 50– 200% in the twenty-first century [2]. Therefore, providing healthy and adequate food to meet the needs of the rapidly growing population owing to growing water scarcity is a global agricultural challenge.

Rice is the second-largest food crop and staple food for 1/3 of the world's population. Compared to other crops, rice is highly sensitive to moisture. Approximately 20% of global rice production is affected by drought during the plant growth cycle, resulting in yield losses of up to 81% [3,4]. Rice plants senesce early during drought stress [5]. Accumulation of osmolytes and organic acids, reduction in photosynthetic efficiency, and changes in carbohydrate metabolism are typical biochemical and physiological drought tolerance responses in rice [6]. The effects of drought on rice vary according to differences in the drought tolerance of the rice varieties, growth stage, duration, and degree of drought stress [7,8]. The grain-filling stage is critical for rice yield and quality. Drought stress leads to the degradation of flowers, sterility of panicles, increase in shriveled grain, and decrease in the grain number of panicles and 1,000-grain weight, thereby reducing rice yield [9,10]. Studies have shown that compared with normal conditions, rice yield decreased by 31–64 and 65–85% under moderate and severe drought stress, respectively [11].

With improvements in living standards, structural reform of the agricultural supply side, policy guidance, and technological progress, the effective supply of rice has changed. Therefore, improving the grain quality after yield has become a major concern in rice breeding programs [12]. Genes mainly control rice quality, and cultivation techniques and environmental conditions significantly affect rice formation [13]. Chalkiness results from poor accumulation of starch and amyloplast formation, where the supply rate and availability of assimilates affect chalkiness [14]. Water deficiency has the greatest effect on chalkiness during the filling stage, causing a significant increase in the rate and degree of chalkiness [15]. During the grain-filling stage, when the soil moisture reached −15 kPa, the rate and degree of chalkiness were not significantly affected. When the soil moisture reached −30 kPa, the chalkiness and gelatinization temperature were increased, and the content of amylose and protein was less affected [16]. Some studies have shown that the eating and cooking quality of rice worsen under continuous drought stress during the grain-filling stage [17,18].

Starch is the most important component of rice, and is divided into amylose and amylopectin. Its synthesis and accumulation are greatly affected by drought. During the filling stage, drought stress limits ADPG pyrophosphatase (AGPase) activity [19] and expression of the *Wx* gene [20], decreases granule-bound starch synthase enzyme (GBSS) activity [21], and enhances branching enzyme (SBE) and soluble starch synthase enzyme (SS) activity [22], which changes the starch content [18,23] and the structure [24]. Gunaratne et al. [17] found that the crystal structure of starch increased and that the change in amylose content was inconsistent under drought stress after anthesis. The impact of drought on varieties with long growth periods is higher than that on varieties with short growth periods. The results showed that starch from different varieties responded differently to drought.

Progress has been made in studying the effects of drought stress on rice during the grain-filling stage. However, the influence of drought on different varieties in past studies differed owing to the different treatment periods, degrees, and durations. Previous studies focused on yield and quality and selected only two or three varieties as test materials, with limited studies on the response of starch to drought during the filling stage. Therefore, to address these limitations, this study selected eight representative *Japonica* rice varieties as test materials to analyze the responses of yield, quality, and starch to different gradients of moisture deficit during the grain-filling stage. Heilongjiang Province is China's largest production base for high-quality *Japonica* rice, but experiences constrained development of rice and food security due to drought. The rice varieties selected for our experiment were high-quality *Japonica* rice varieties, mainly grown in the first and second accumulated temperature zones of Heilongjiang Province, with stable traits and large planting areas. This study aimed to improve the research basis for drought tolerance of *Japonica* rice in cold regions, ensure an increased and stable yield of rice, maintain and improve rice quality under drought conditions, and promote the sustainable development of agriculture.

2 Materials and methods

2.1 Experimental design

The test was conducted in potted experimental fields (26°10′ N, 119°23′E) at Heilongjiang Bayi Agricultural University in 2019. Sowing was performed on April 18 and the rice seedlings were transplanted into plastic buckets with a diameter of 30 cm on May 20. A completely randomized experimental design was used. The planting areas of the eight high-quality *Japonica* rice varieties selected in the experiment were large, and the varieties were representative (Table 1). The quality of Longdao18 reached the first level of the national "high-quality rice" standard. Kenjing8 was bred by our research group, and the comprehensive resistance was strong. Four levels of water stress were tested: CK, normal irrigation, with soil moisture of 0 kPa, and D1, D2, and D3, with soil moisture of −10 ± 2, −25 ± 2, and −40 ± 2 kPa,

Table 1: Material characteristics

Variety		Taste evaluation	Grain type	Active accumulated temperature (°C)	Accumulated temperature zone
LD18	Longdao18	First grade	Long	2,600	First accumulated temperature zone
KJ8	Kenjing8	Secondary grade	Round	2,650	
SJ9	Songjing9	Secondary grade	Long	2,650	
SJ22	Songjing22	Secondary grade	Long	2,700	
LJ21	Longjing21	Secondary grade	Long	2,516	Second accumulated temperature zone
SJ18	Suijing18	Secondary grade	Long	2,450	
KJ7	Kenjing7	Secondary grade	Round	2,575	
LD5	Longdao5	Secondary grade	Round	2,500	

Information from China Rice Data Center, https://www.ricedata.cn/.

Table 2: Nutrient content of experimental soil

Soil type	Total nitrogen (g/kg)	Total phosphorus (g/kg)	Total potassium (g/kg)	Organic matter (g/kg)	Available nitrogen (mg/kg)	Available phosphorus (mg/kg)	Available potassium (mg/kg)
Albic soil	1.52	0.65	18.88	27.86	158.64	53.85	110.99

respectively. Drought was imposed for 21 days by withholding the applied water at the beginning of the anthesis stage. The test was performed three times, with each repetition of 15 pots, four holes per pot, and three seedlings per hole. An artificial moisture control method was used and a rain shelter was opened on sunny days. Soil water potential was monitored using a negative-pressure soil moisture meter (3–55, Kuake, China), which was read 6–10 times a day. According to the meter index, the potted plants were replenished in time. Fertilizer management for the treatments and control was performed according to conventional local production fields. The soil used in the experiment was albic soil, and its physicochemical properties are listed in Table 2. An automatic microclimate observation system (RR-9100, Rainroot Scientific, China) was used to observe the daily average temperature and moisture content of the potted plants from July to August (Figure 1).

2.2 Determination and data collection

2.2.1 Determination of yield and composition factors

In mid-September, harvesting was carried out sequentially according to the growth period of the varieties. The panicle number of the 16 holes was continuously monitored for each treatment. Based on the average panicle number, four holes were selected for natural air-drying and used to determine grain number, seed setting rate, and 1,000-grain weight.

2.2.2 Appearance quality

The harvested rice was placed for 3 months and threshed using a small threshing machine. Brown (FC2K, YAMAMOTO, Japan) and milled rice machines (VP-32, YAMAMOTO, Japan) were used to process the rice into milled rice. Appearance quality was measured using a rice appearance quality identification instrument (EM-1000, SATAKE, Japan). The measurement indicators included the chalkiness rate, chalkiness degree, and length–width ratio.

2.2.3 Nutritional quality

A small reducing machine was used to grind the milled rice into flour. Rice flour (2.00 g) was used for digestion and nitrogen content was determined using a Kjeldahl nitrogen analyzer (K1100, Hanon, China). A conversion factor (5.95) was used to calculate rice protein content.

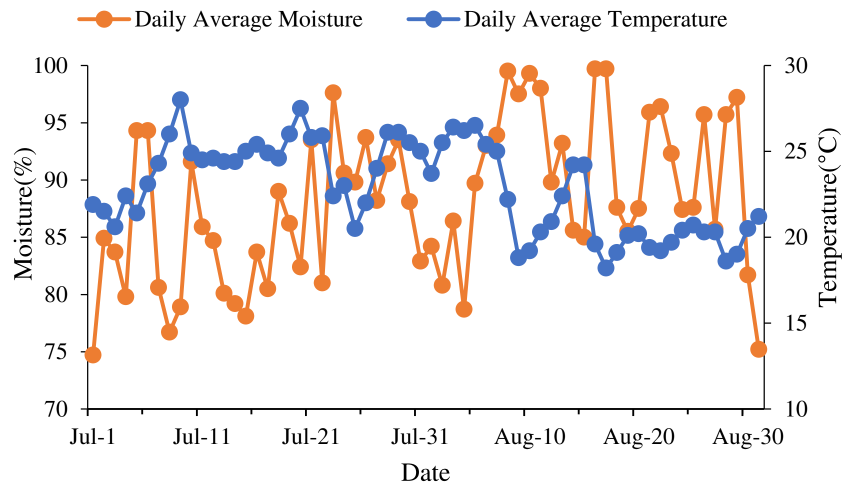

Figure 1: Daily temperature and moisture from July to August.

The extraction and measurement of rice protein composition followed the method described by Fan et al. [25]. Milled rice flour (100 mg) was placed in a 1.5 centrifugal tube, extracted by shaking with 1 mL of distilled water for 4 h, and centrifuged at 10,000 rpm for 20 min. The supernatant was then placed in a centrifuge tube. The extraction was repeated three times to extract all the albumin. All supernatants were combined and analyzed using a modified Bradford Protein Assay Kit. After water extraction, 1 mL of 5% NaCl, 1 mL of 70% ethanol, and 1 mL of 0.2% NaOH were used to extract globulin, prolamin, and glutelin, respectively. The extraction and determination processes were similar to those used for albumin determination.

2.2.4 Eating and cooking quality

The eating and cooking quality of the rice were measured using a rice taste meter (STA-1A, SATAKE, Japan). The aroma, gloss, integrity, taste, and palatability of *Japonica* rice standards were used to evaluate taste quality. The specific test method is described by Fan et al. [25].

2.2.5 Gel consistency

The gel consistency was determined according to the National Standard of the People's Republic of China-GB/T 17891-1999.

2.2.6 Rapid viscosity analyzer profiles

The viscosity of the cooked rice was analyzed using a rapid viscosity analyzer (RVA; Newport Scientific, Australia) to obtain the RVA profiles. The operation was based on the standard method AACC61-02. The RVA profiles were characterized by peak viscosity (PKV), hot paste viscosity (HPV), cool paste viscosity (CPV), breakdown viscosity (BDV) = PKV−HPV, setback viscosity (SBV) = CPV−PKV, recovery viscosity (CSV) = CPV−HPV, and pasting temperature (PT).

2.2.7 Amylopectin structure

Starch extraction and debranching were based on the method described by Hasjim et al. [26] with modifications. The debranched starch was labeled with 8-aminopyrene-1,3,6, trisulfonic acid as described by Wu et al. [27]. The structure of the debranched amylopectin was characterized using a PA-800 Plus FACE (Beckman-Coulter) system. According to the classification method of Hanashiro et al. [28], amylopectin chains can be divided into four types: Fa (DP 6-12), Fb1 (DP 13-24), Fb2 (DP 25-36), and Fb3 (DP 37-60).

2.3 Statistical analysis

Excel 2003 was used to sort and draw the data. DPS v7.05 software was used for the analysis of variance and Duncan's test was applied to identify the significance of the treatments.

3 Results

3.1 Yield and components analysis

The differences in 1,000-grain weight, seed setting rate, and grain yield between the different varieties and drought treatments were extremely significant (Table 3). The yield of LD18 was the highest. Water deficit significantly reduced

Table 3: Comparison of *Japonica* rice yield among different treatments

Variety	Treatment	Grain number per panicle	1,000-grain weight (g)	Seed setting rate (%)	Yield per hole (g)
LD18	CK	81.83 ± 3.06ab	25.13 ± 0.38a	94.43 ± 0.03a	29.26 ± 0.67ab
	D1	73.16 ± 4.02b	25.26 ± 0.35a	87.94 ± 0.96b	24.38 ± 1.43c
	D2	78.65 ± 1.83ab	25.11 ± 0.23a	88.52 ± 1.25b	26.23 ± 0.92bc
	D3	85.12 ± 3.32a	26.18 ± 0.54a	92.21 ± 1.15a	30.49 ± 1.17a
KJ8	CK	73.17 ± 0.28a	23.74 ± 0.13a	96.78 ± 0.43a	23.49 ± 0.27a
	D1	81.61 ± 2.82a	22.42 ± 0.25c	96.21 ± 0.59a	24.63 ± 0.68a
	D2	78.98 ± 3.04a	22.96 ± 0.33bc	97.39 ± 0.77a	24.70 ± 0.69a
	D3	81.32 ± 3.38a	23.65 ± 0.12ab	97.51 ± 0.84a	25.55 ± 0.77a
SJ9	CK	91.37 ± 1.28ab	24.48 ± 0.07a	90.76 ± 2.34a	28.40 ± 0.42a
	D1	98.67 ± 2.76a	24.34 ± 0.29a	85.75 ± 2.2ab	28.86 ± 1.43a
	D2	87.46 ± 2.68b	23.85 ± 0.55a	82.31 ± 2.89b	24.10 ± 0.75b
	D3	90.58 ± 2.61ab	24.90 ± 0.25a	84.26 ± 2.14ab	26.62 ± 1.21ab
SJ22	CK	73.61 ± 2.99a	29.10 ± 0.19a	87.28 ± 1.17a	24.30 ± 1.02a
	D1	74.18 ± 3.02a	27.66 ± 0.77a	83.66 ± 0.94ab	22.29 ± 0.86a
	D2	77.56 ± 1.92a	27.44 ± 0.70a	81.08 ± 1.60b	22.41 ± 0.65a
	D3	73.35 ± 2.97a	28.92 ± 0.16a	83.34 ± 0.96ab	22.33 ± 0.51a
LJ21	CK	72.87 ± 1.36a	26.56 ± 0.41a	94.31 ± 1.89a	24.09 ± 0.75a
	D1	72.47 ± 1.35a	25.64 ± 0.12a	93.40 ± 1.78a	22.56 ± 0.51ab
	D2	72.38 ± 1.78a	25.26 ± 0.51a	93.12 ± 1.46a	22.13 ± 0.81ab
	D3	66.64 ± 2.12b	25.92 ± 0.40a	93.66 ± 1.47a	21.04 ± 0.95b
SJ18	CK	75.36 ± 1.74a	25.72 ± 0.21a	92.88 ± 0.17a	25.20 ± 0.53a
	D1	75.91 ± 3.19a	24.77 ± 0.31b	92.92 ± 1.20a	24.43 ± 0.73a
	D2	78.08 ± 3.27a	24.46 ± 0.07b	93.90 ± 0.26a	25.11 ± 1.08a
	D3	75.38 ± 3.89a	24.65 ± 0.09b	94.33 ± 0.54a	24.53 ± 1.18a
KJ7	CK	92.99 ± 1.31a	22.86 ± 0.20a	96.13 ± 0.61a	26.78 ± 0.42a
	D1	86.61 ± 0.69bc	22.68 ± 0.35a	93.71 ± 0.75b	23.93 ± 0.38b
	D2	89.44 ± 0.99ab	22.18 ± 0.45a	93.78 ± 0.80ab	24.21 ± 0.94b
	D3	83.99 ± 1.75c	22.89 ± 0.32a	95.17 ± 0.60ab	23.79 ± 0.62b
LD5	CK	69.22 ± 2.53ab	24.36 ± 0.42a	96.44 ± 0.32a	24.39 ± 0.91a
	D1	70.01 ± 1.64a	23.76 ± 0.15a	95.24 ± 0.55ab	23.76 ± 0.57a
	D2	63.25 ± 1.68c	24.80 ± 0.33a	96.38 ± 0.65a	22.66 ± 0.48ab
	D3	63.65 ± 0.49bc	23.68 ± 0.75a	93.92 ± 0.92b	21.24 ± 0.77b
F value	Variety	47.61**	84.60**	55.48**	18.42**
	Treatment	0.55 ns	8.39**	7.82**	6.10**
	$V \times T$	2.50**	1.37ns	1.83*	2.93**

Different letters indicate significant differences among the treatments ($P < 0.05$). *, **, and ns indicate significances at $P < 0.05$, $P < 0.01$, and non-significant, respectively. The same as below.

the grain number per panicle of LJ21, KJ7, and LD5; 1,000-grain weight of KJ8 and SJ18; seed setting rate of LD18, SJ9, SJ22, KJ7, and LD5; and grain yield of LD18, SJ9, LJ21, KJ7, and LD5. A comprehensive analysis showed that different degrees of water deficit negatively impacted yield. The seed setting rate and yield of the other varieties showed a downward trend, except for those of KJ8 and SJ18. Water deficit had a greater impact on the seed setting rate, which in turn reduced the yield.

3.2 Appearance quality analysis

Differences in appearance among the cultivars and drought treatments were significant (Figure 2). KJ8 had the best appearance quality and the smallest length–width ratio. The grain length–width ratio was less affected by water stress. The rate and degree of chalkiness increased significantly in the order D1 > D2 > D3 > CK. The appearance quality of rice decreased markedly under water-deficient conditions during the grain-filling stage.

3.3 Nutritional quality analysis

Under water stress, the total protein content of the different varieties showed in the following CK > D1 > D2 > D3 (Table 4). The albumin content showed an increasing trend, except for KJ8, KJ7, and LD5. The globulin content of

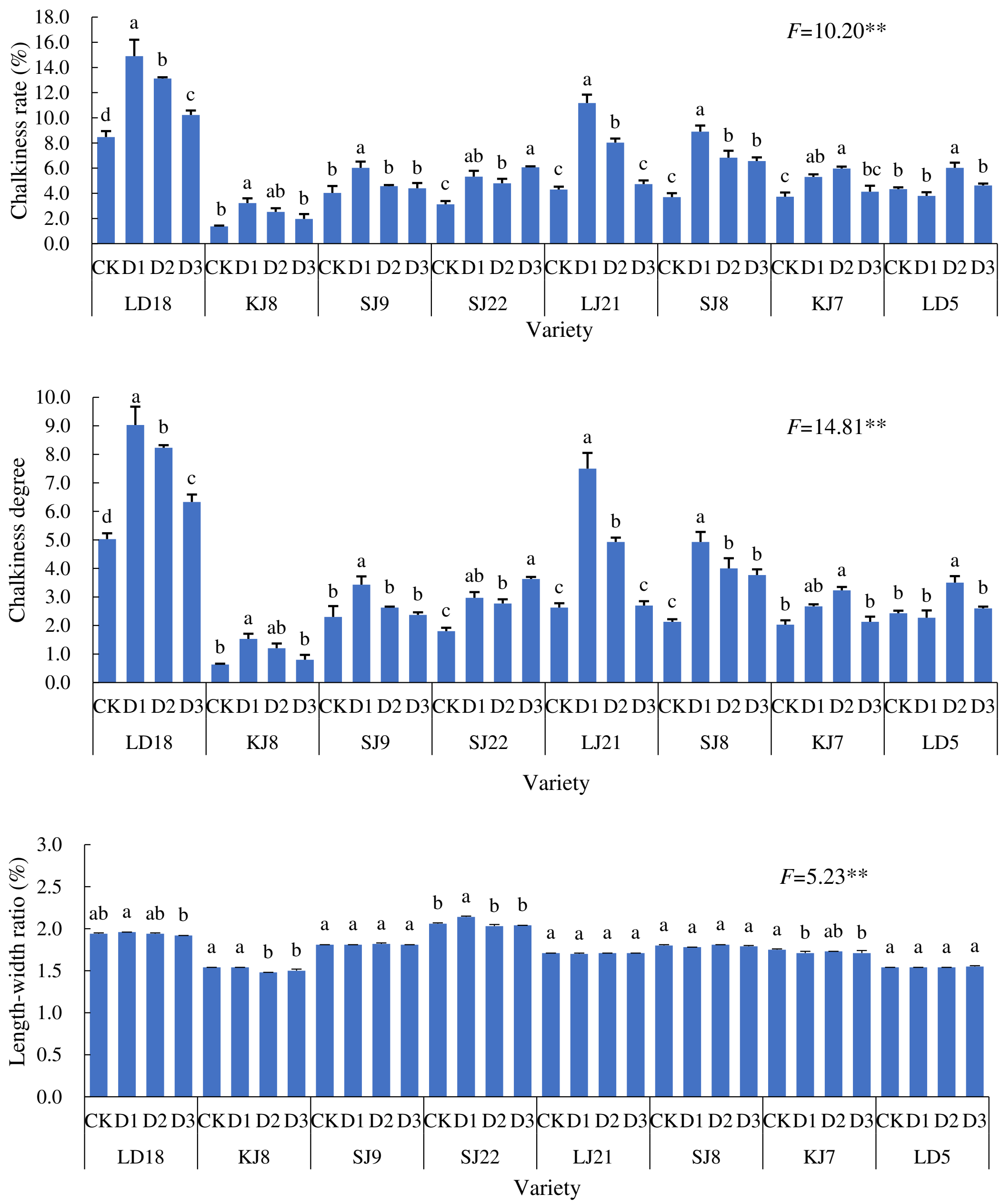

Figure 2: Comparison of appearance quality among different treatments.

LJ8, SJ18, and KJ7 showed a significant decreasing trend, whereas those of SJ22, LJ21, and LD5 showed the opposite trend. Drought treatments had little effect on the prolamin content of KJ7 and LD5, improved the content of KJ8, and decreased the content of other varieties. The glutelin content of LD18, SJ22, LJ21, and LD5 decreased to varying degrees, whereas that of KJ8, SJ18, and KJ7 increased. Comprehensive analysis showed that water deficit reduced the total protein content of rice. The protein components content of different varieties responded differently to drought and the effect of moderate and severe drought treatments on protein content was greater than that of mild stress.

3.4 RVA characteristics analysis

The effect of water stress on RVA characteristic values was significant (Table 5). Under drought treatments, PKV, HPV,

Table 4: Comparison of nutritional quality among different treatments

Variety	Treatment	Total protein (%)	Albumin (%)	Globulin (%)	Prolamin (%)	Glutelin (%)
LD18	CK	6.11 ± 0.02a	5.23 ± 0.10b	10.41 ± 0.08a	5.25 ± 0.18a	79.12 ± 0.17a
	D1	5.89 ± 0.07b	5.62 ± 0.17b	10.56 ± 0.03a	4.93 ± 0.15ab	78.89 ± 0.34a
	D2	5.86 ± 0.01b	6.76 ± 0.11a	10.63 ± 0.31a	5.03 ± 0.05ab	77.58 ± 0.40b
	D3	5.48 ± 0.04c	5.43 ± 0.16b	10.86 ± 0.15a	4.56 ± 0.16b	79.16 ± 0.16a
KJ8	CK	6.32 ± 0.11ab	8.83 ± 0.15a	15.12 ± 0.46a	4.02 ± 0.07c	72.03 ± 0.43c
	D1	6.42 ± 0.08a	7.99 ± 0.11b	15.10 ± 0.14a	4.54 ± 0.14b	72.37 ± 0.28c
	D2	5.98 ± 0.06c	8.56 ± 0.06a	11.20 ± 0.25b	5.61 ± 0.17a	74.63 ± 0.24b
	D3	6.02 ± 0.12bc	8.64 ± 0.21a	10.73 ± 0.19b	4.51 ± 0.20bc	76.12 ± 0.38a
SJ9	CK	5.98 ± 0.23a	5.61 ± 0.25b	11.98 ± 0.20a	4.73 ± 0.15a	77.68 ± 0.54a
	D1	5.72 ± 0.18ab	6.91 ± 0.52a	12.44 ± 0.34a	4.79 ± 0.26a	75.87 ± 0.96a
	D2	5.30 ± 0.10b	6.63 ± 0.14ab	11.68 ± 0.15a	3.72 ± 0.11b	77.96 ± 0.17a
	D3	5.82 ± 0.15ab	7.69 ± 0.31a	11.79 ± 0.24a	3.90 ± 0.23b	76.62 ± 0.62a
SJ22	CK	6.15 ± 0.02a	5.79 ± 0.14b	12.35 ± 0.14b	5.27 ± 0.07a	76.59 ± 0.26a
	D1	5.91 ± 0.02b	5.68 ± 0.11b	13.11 ± 0.26b	5.01 ± 0.08ab	76.21 ± 0.44a
	D2	5.76 ± 0.03c	7.19 ± 0.22a	15.44 ± 0.75a	5.12 ± 0.21ab	72.25 ± 0.97b
	D3	5.63 ± 0.01d	6.11 ± 0.23b	13.00 ± 0.14b	4.66 ± 0.14b	76.23 ± 0.12a
LJ21	CK	7.48 ± 0.04a	4.03 ± 0.14b	11.48 ± 0.22b	4.31 ± 0.12a	80.18 ± 0.34a
	D1	6.84 ± 0.16b	5.08 ± 0.05a	12.03 ± 0.23b	3.69 ± 0.11b	79.20 ± 0.36ab
	D2	6.84 ± 0.10b	4.62 ± 0.23ab	11.89 ± 0.30b	4.08 ± 0.11ab	79.40 ± 0.62ab
	D3	6.58 ± 0.07b	4.65 ± 0.37ab	13.80 ± 0.96a	4.42 ± 0.18a	77.12 ± 1.38b
SJ18	CK	6.45 ± 0.06ab	3.89 ± 0.25c	12.81 ± 0.65a	3.22 ± 0.12a	80.08 ± 0.96b
	D1	6.73 ± 0.15a	4.32 ± 0.22bc	10.53 ± 0.25b	2.72 ± 0.14b	82.43 ± 0.50a
	D2	6.79 ± 0.09a	4.95 ± 0.26b	12.44 ± 0.33a	3.13 ± 0.17ab	79.48 ± 0.76b
	D3	6.14 ± 0.11b	6.42 ± 0.17a	11.86 ± 0.33ab	3.19 ± 0.08a	78.53 ± 0.47b
KJ7	CK	7.17 ± 0.03a	6.79 ± 0.18a	11.19 ± 0.11a	4.98 ± 0.07a	77.04 ± 0.27b
	D1	7.18 ± 0.03a	6.68 ± 0.31a	11.49 ± 0.44a	5.07 ± 0.12a	76.76 ± 0.79b
	D2	6.91 ± 0.02b	5.51 ± 0.15b	10.20 ± 0.20b	4.96 ± 0.03a	79.33 ± 0.14a
	D3	7.17 ± 0.02a	6.61 ± 0.17a	10.81 ± 0.16ab	4.87 ± 0.14a	77.70 ± 0.31b
LD5	CK	6.62 ± 0.02a	8.42 ± 0.32a	12.44 ± 0.40c	6.23 ± 0.06a	72.90 ± 0.40a
	D1	6.57 ± 0.09a	8.70 ± 0.17a	14.80 ± 0.36a	6.61 ± 0.18a	69.90 ± 0.59b
	D2	6.22 ± 0.04b	9.06 ± 0.06a	13.90 ± 0.20ab	6.37 ± 0.37a	70.67 ± 0.59b
	D3	6.06 ± 0.03b	7.49 ± 0.28b	13.66 ± 0.25b	6.28 ± 0.05a	72.57 ± 0.57a
F value	Variety	108.08**	125.58**	28.63**	54.11**	28.03**
	Treatment	59.96**	24.59**	3.37*	4.24**	0.88 ns
	V × *T*	14.44**	9.37**	7.62**	4.79**	2.38**

Protein component content is the percentage of each protein component to total protein content.

BDV, and CPV of LD18 showed a trend of first decreasing and then increasing; KJ8 showed the opposite trend; and PKV, HPV, SBV, CPV, and CSV of LD5 increased significantly. The PKV, HPV, and CPV of SJ9 were significantly reduced under the D1 treatment, and BDV and CSV were significantly improved under the D2 treatment. D1 treatment decreased the PKV and BDV of SJ22, whereas D3 treatment significantly decreased SBV and increased PT. The overall analysis showed that the effects of drought treatment on LJ21, SJ18, KJ7, and PT were relatively small, whereas the effects of the D1 and D3 treatments on the RVA characteristic values were different.

3.5 Eating and cooking quality analysis

The results showed that the effects of variety and drought treatment on taste quality were significant, with the taste quality of LD18 being the best (Table 6). Water stress reduced the gel consistency. The gloss, taste, palatability, and comprehensive scores of LD18, KJ8, LJ21, and LD5 were significantly improved, whereas the integrity of LJ21 and LD5 decreased under the D2 and D3 treatments. Drought treatment significantly reduced the gloss and taste of SJ18, and the D3 treatment significantly reduced the aroma, palatability, and comprehensive score. Comprehensive

Table 5: Comparison of RVA characteristics among different treatments

Variety	Treatment	PKV (cP)	HPV (cP)	BDV (cP)	SBV (cP)	CPV (cP)	CSV (cP)	PT (°C)
LD18	CK	3,274 ± 41b	2,656 ± 21a	618 ± 53b	269 ± 55b	3,543 ± 57b	887 ± 11c	69.92 ± 0.26a
	D1	3,177 ± 7c	2,585 ± 6b	592 ± 11b	336 ± 20a	3,513 ± 19b	928 ± 14b	69.98 ± 0.25a
	D2	3,057 ± 25d	2,532 ± 28b	525 ± 17c	360 ± 10a	3,417 ± 18c	885 ± 13c	70.20 ± 0.03a
	D3	3,412 ± 8a	2,678 ± 4a	734 ± 6a	263 ± 13b	3,675 ± 5a	997 ± 7a	70.15 ± 0.03a
KJ8	CK	3,272 ± 49b	2,010 ± 17ab	1,262 ± 64b	−278 ± 34a	3,040 ± 1a	1,030 ± 16b	71.03 ± 0.03b
	D1	3,284 ± 22b	2,022 ± 11ab	1,262 ± 12b	−268 ± 14a	3,016 ± 8a	994 ± 7bc	71.87 ± 0.03a
	D2	3,439 ± 33a	2,024 ± 36a	1,414 ± 13a	335 ± 16ab	3,103 ± 43a	1,079 ± 7a	71.53 ± 0.29ab
	D3	3,258 ± 50b	1,945 ± 18b	1,312 ± 55ab	−386 ± 23b	2,914 ± 29b	969 ± 18c	71.55 ± 0.26ab
SJ9	CK	3,303 ± 81a	2,738 ± 56a	564 ± 25b	368 ± 23b	3,670 ± 58a	932 ± 2b	71.83 ± 0.06a
	D1	2,990 ± 36b	2,466 ± 38b	524 ± 4b	442 ± 17a	3,432 ± 21b	966 ± 17ab	71.27 ± 0.24ab
	D2	3,310 ± 40a	2,624 ± 18a	686 ± 27a	339 ± 19b	3,649 ± 28a	1,025 ± 23a	70.82 ± 0.21b
	D3	3,213 ± 85a	2,625 ± 59a	588 ± 29b	361 ± 27b	3,574 ± 64ab	949 ± 24b	71.28 ± 0.26ab
SJ22	CK	3,162 ± 10a	1,752 ± 14a	1,410 ± 25a	−321 ± 10b	2,842 ± 16a	1,090 ± 10a	71.82 ± 0.04b
	D1	2,914 ± 107b	1,747 ± 57a	1,167 ± 4b	−114 ± 38a	2,800 ± 73a	1,053 ± 19a	71.87 ± 0.03b
	D2	3,252 ± 100a	1,792 ± 6a	1,460 ± 27a	−355 ± 63bc	2,898 ± 38a	1,105 ± 34a	72.20 ± 0.25b
	D3	3,347 ± 5a	1,812 ± 9a	1,536 ± 29a	−468 ± 13c	2,880 ± 8a	1,068 ± 1a	72.70 ± 0.03a
LJ21	CK	3,741 ± 34b	2,727 ± 58b	1,014 ± 160a	163 ± 104a	3,903 ± 45bc	1,176 ± 56a	73.13 ± 0.27a
	D1	3,762 ± 42ab	2,732 ± 12b	1,031 ± 54a	96 ± 30a	3,858 ± 12c	1,126 ± 24a	72.73 ± 0.01a
	D2	3,832 ± 21ab	2,891 ± 36a	941 ± 16a	162 ± 6a	3,994 ± 27a	1,103 ± 10a	73.05 ± 0.23a
	D3	3,880 ± 43a	2,771 ± 41ab	1,110 ± 84a	90 ± 46a	3,970 ± 15ab	1,199 ± 40a	73.25 ± 0.30a
SJ18	CK	3,657 ± 49ab	2,952 ± 47a	704 ± 68a	178 ± 53b	3,835 ± 58a	882 ± 28b	72.92 ± 0.27ab
	D1	3,587 ± 26b	2,954 ± 29a	633 ± 3a	317 ± 10a	3,904 ± 25a	950 ± 10a	73.55 ± 0.03a
	D2	3,669 ± 87ab	3,048 ± 39a	654 ± 61a	201 ± 41b	3,903 ± 50a	855 ± 20b	73.23 ± 0.27ab
	D3	3,774 ± 66a	2,953 ± 34a	756 ± 34a	227 ± 9b	3,935 ± 57a	982 ± 25a	72.67 ± 0.02b
KJ7	CK	3,086 ± 17a	2,545 ± 17a	540 ± 12a	400 ± 12b	3,486 ± 18a	941 ± 13a	71.03 ± 0.02a
	D1	3,065 ± 48a	2,549 ± 43a	516 ± 8a	357 ± 10c	3,422 ± 51a	872 ± 17a	71.02 ± 0.02a
	D2	3,038 ± 7a	2,506 ± 34a	532 ± 28a	443 ± 3a	3,481 ± 7a	975 ± 28a	71.28 ± 0.26a
	D3	3,076 ± 38a	2,456 ± 78a	620 ± 56a	362 ± 13c	3,438 ± 30a	982 ± 68a	70.80 ± 0.28a
LD5	CK	2,821 ± 2c	2,349 ± 3b	473 ± 5a	411 ± 3b	3,232 ± 4c	883 ± 8b	70.95 ± 0a
	D1	2,933 ± 21b	2,451 ± 15b	482 ± 13a	502 ± 2a	3,435 ± 22b	984 ± 13a	70.73 ± 0.29a
	D2	2,934 ± 11b	2,451 ± 30b	482 ± 21a	446 ± 21ab	3,380 ± 32b	928 ± 9ab	71.27 ± 0.27a
	D3	3,121 ± 41a	2,607 ± 54a	514 ± 13a	458 ± 32ab	3,578 ± 49a	971 ± 30a	70.72 ± 0.26a
F value	Variety	146.90**	573.47**	415.58**	564.95**	494.55**	56.71**	113.34**
	Treatment	15.99**	3.81**	14.43**	18.22**	7.56**	4.25**	0.47ns
	$V \times T$	4.50**	4.57**	3.09**	5.38**	6.15**	4.35**	2.74**

PKV, peak viscosity; HPV, hot paste viscosity; BDV, breakdown viscosity; SBV, setback viscosity; CPV, cool paste viscosity; CSV, recovery viscosity; PT, pasting temperature.

analysis indicated that gel consistency was decreased by drought stress, the comprehensive scores of LD18, KJ8, LJ21, and LD5 improved under moderate and severe drought treatments, and the comprehensive score of SJ18 decreased. The taste quality of KJ7 and SJ22 was less affected by drought.

3.6 Amylopectin structure analysis

Water deficit significantly reduced the ∑Fa of LJ21. The ∑Fa of KJ7 increased and decreased under D1 and D2 treatments, respectively (Table 7). The ∑Fb1 of LD18 and LJ21 significantly improved and decreased under D1 treatment, the ∑Fb1 of LD18 reduced and that of LJ21 and SJ18 significantly increased under D3 treatment. ∑Fb2 of LD18 markedly decreased and that of LJ21 and SJ18 significantly improved under drought. The ∑Fb3 of LD18 and KJ7 significantly decreased and SJ18 increased under D1 and D2 treatments and that of LD18, LJ21, and KJ7 increased and SJ18 decreased under D3 treatment. Drought treatment significantly improved ACLFb2 and ACLAP in SJ18. The results indicated that the effect of drought on average chain length was relatively small. The effects of D1 and D3 treatments on

Table 6: Comparison of eating and cooking quality among different treatments

Variety	Treatment	Aroma	Gloss	Integrity	Taste	Palatability	Comprehensive score	Gel consistency (cm)
LD18	CK	7.45 ± 0.03a	8.60 ± 0.16b	6.73 ± 0.02ab	8.43 ± 0.06c	8.45 ± 0.19b	87.85 ± 0.61b	9.30 ± 0.26a
	D1	7.50 ± 0a	8.98 ± 0.05a	6.78 ± 0.02a	8.50 ± 0bc	8.88 ± 0.09a	88.75 ± 0.20b	8.60 ± 0.06b
	D2	7.55 ± 0.03a	9.28 ± 0.08a	6.63 ± 0.03b	8.60 ± 0ab	9.18 ± 0.07a	90.30 ± 0.13a	7.83 ± 0.09c
	D3	7.48 ± 0.05a	9.18 ± 0.14a	6.63 ± 0.03b	8.63 ± 0.03a	9.05 ± 0.21a	90.33 ± 0.41a	8.87 ± 0.12ab
KJ8	CK	7.4 ± 0.04b	8.20 ± 0.13bc	7.08 ± 0.02a	8.40 ± 0.05b	8.08 ± 0.18bc	85.88 ± 0.42b	7.80 ± 0.09a
	D1	7.38 ± 0.03b	7.98 ± 0.07c	7.10 ± 0.04a	8.25 ± 0.03b	7.85 ± 0.15c	85.00 ± 0.43b	7.40 ± 0.18a
	D2	7.53 ± 0.02a	8.47 ± 0.03ab	7.00 ± 0.04a	8.50 ± 0.05ab	8.33 ± 0.03ab	87.15 ± 0.44a	7.78 ± 0.14a
	D3	7.50 ± 0.04a	8.63 ± 0.09a	7.00 ± 0.04a	8.53 ± 0.03a	8.58 ± 0.13a	87.75 ± 0.21a	7.50 ± 0.06a
SJ9	CK	7.43 ± 0.02ab	8.15 ± 0.06bc	6.88 ± 0.03ab	8.25 ± 0.03a	8.03 ± 0.09ab	85.33 ± 0.13a	8.17 ± 0.03a
	D1	7.37 ± 0.03b	7.90 ± 0.15c	6.93 ± 0.06a	8.07 ± 0.03b	7.73 ± 0.15b	83.50 ± 0.80b	8.20 ± 0.12a
	D2	7.50 ± 0.04a	8.50 ± 0.16a	6.83 ± 0.03b	8.35 ± 0.07a	8.35 ± 0.19a	86.38 ± 0.44a	7.60 ± 0.12b
	D3	7.43 ± 0.05ab	8.23 ± 0.18ab	6.95 ± 0.09a	8.28 ± 0.07a	8.10 ± 0.24ab	86.13 ± 0.50a	7.90 ± 0.20ab
SJ22	CK	7.53 ± 0.02b	8.50 ± 0.07bc	6.88 ± 0.03a	8.43 ± 0.03ab	8.28 ± 0.09ab	86.28 ± 0.13a	8.47 ± 0.09a
	D1	7.68 ± 0.03a	8.85 ± 0.10a	6.93 ± 0.02a	8.53 ± 0.03a	8.63 ± 0.14a	86.90 ± 0.35a	8.53 ± 0.07a
	D2	7.53 ± 0.02b	8.33 ± 0.09c	6.98 ± 0.02a	8.35 ± 0.03b	8.15 ± 0.14b	85.67 ± 0.35a	7.90 ± 0.13b
	D3	7.53 ± 0.05b	8.73 ± 0.03ab	6.90 ± 0.04a	8.48 ± 0.03a	8.48 ± 0.12ab	86.78 ± 0.30a	8.00 ± 0.12b
LJ21	CK	7.45 ± 0.03b	8.10 ± 0.07b	7.05 ± 0.03a	8.33 ± 0.03b	7.93 ± 0.11b	84.80 ± 0.35b	7.15 ± 0.13a
	D1	7.47 ± 0.08b	8.13 ± 0.16b	7.00 ± 0a	8.18 ± 0.10c	7.78 ± 0.28b	83.80 ± 0.94b	6.68 ± 0.11ab
	D2	7.50 ± 0.04b	8.67 ± 0.03a	6.88 ± 0.05b	8.45 ± 0.06a	8.47 ± 0.03a	87.33 ± 0.15a	6.78 ± 0.18ab
	D3	7.60 ± 0.04a	8.65 ± 0.09a	6.90 ± 0b	8.50 ± 0a	8.40 ± 0.08a	86.60 ± 0.11a	6.63 ± 0.06b
SJ18	CK	7.53 ± 0.05a	8.40 ± 0.16a	6.98 ± 0.02b	8.40 ± 0.07a	8.18 ± 0.21a	85.58 ± 0.44a	8.55 ± 0.17a
	D1	7.45 ± 0.03a	8.05 ± 0.12b	7.05 ± 0.03b	8.25 ± 0.06b	7.88 ± 0.13a	84.73 ± 0.35a	7.57 ± 0.23b
	D2	7.45 ± 0.03a	8.08 ± 0.07b	7.03 ± 0.05b	8.25 ± 0.03b	7.85 ± 0.07a	84.30 ± 0.41a	6.98 ± 0.16c
	D3	7.23 ± 0.02b	7.50 ± 0.14c	7.18 ± 0.03a	8.10 ± 0.05c	7.23 ± 0.03b	81.67 ± 0.12b	7.87 ± 0.27b
KJ7	CK	7.53 ± 0.02a	7.98 ± 0.09a	7.10 ± 0a	8.25 ± 0.03a	7.70 ± 0.09a	82.13 ± 0.38a	8.15 ± 0.06ab
	D1	7.50 ± 0.04a	7.98 ± 0.13a	7.10 ± 0.04a	8.20 ± 0.05a	7.70 ± 0.15a	82.10 ± 0.67a	7.78 ± 0.17b
	D2	7.55 ± 0.03a	8.05 ± 0.09a	7.05 ± 0.03a	8.28 ± 0.06a	7.73 ± 0.12a	83.00 ± 0.61a	8.58 ± 0.13a
	D3	7.58 ± 0.02a	8.10 ± 0.11a	7.13 ± 0.05a	8.30 ± 0.05a	7.83 ± 0.14a	82.80 ± 0.67a	7.73 ± 0.08b
LD5	CK	7.55 ± 0.03a	8.13 ± 0.09b	7.08 ± 0.02a	8.30 ± 0.05b	7.90 ± 0.12b	84.05 ± 0.64b	8.80 ± 0.15a
	D1	7.63 ± 0.05a	8.60 ± 0.15a	6.95 ± 0.03b	8.48 ± 0.06a	8.38 ± 0.19a	86.18 ± 0.40a	7.20 ± 0.31b
	D2	7.65 ± 0.03a	8.68 ± 0.09a	6.95 ± 0.03b	8.53 ± 0.03a	8.23 ± 0.03ab	86.28 ± 0.29a	8.40 ± 0.06a
	D3	7.58 ± 0.02a	8.68 ± 0.08a	6.90 ± 0b	8.48 ± 0.03a	8.40 ± 0.14a	86.68 ± 0.28a	7.35 ± 0.14b
F value	Variety	13.71**	36.37**	55.41**	29.82**	31.12**	78.81**	52.46**
	Treatment	3.20*	8.23**	5.50**	11.82**	6.31**	14.69**	27.33**
	V × *T*	4.14**	5.80**	3.33**	6.33**	4.36**	6.07**	7.83**

chain length distribution were different and the chain length distribution of different varieties showed different responses to drought during the filling stage.

4 Discussion

4.1 Effects of water stress on rice yield

Drought stress has a detrimental effect on rice yield by disrupting the normal molecular, metabolic, and physiological regulatory networks of plant development [29]. The reproductive growth stage of rice is most sensitive to drought [30]. During the filling stage, the seed setting rate and 1,000-grain weight increased under mild stress and the 1,000-grain weight and yield decreased with an increase in the degree of drought [31]. This study showed that drought stress reduced rice yield to varying degrees by reducing the seed setting rate of grains during the grain-filling stage. Rice yield composition is mainly determined by the carbohydrates stored in the stem before heading and the photosynthetic accumulation product after heading [32]. Drought stress reduces photosynthesis in rice leaves, changes the activity of auxins and gibberellins, and hinders assimilate transport. Concurrently, the activity of some key enzymes in the sucrose–starch anabolic metabolism of grains decreases rapidly in the late grain-filling stage,

Table 7: Comparison of amylopectin structure among different treatments

Variety	Treatment	∑Fa (%)	∑Fb1 (%)	∑Fb2 (%)	∑Fb3 (%)	ACLFa	ACLFb1	ACLFb2	ACLFb3	ACLAP
LD18	CK	35.32 ± 0.28a	56.97 ± 0.15b	5.42 ± 0.11a	2.38 ± 0.21b	10.14 ± 0.03b	16.85 ± 0.05a	28.83 ± 0.02ab	45.40 ± 0.09a	16.04 ± 0.15a
	D1	35.24 ± 0.20a	60.16 ± 0.03a	4.94 ± 0.17b	1.07 ± 0.03d	10.80 ± 0.05a	16.63 ± 0.08a	28.75 ± 0.05b	44.43 ± 0.04a	15.19 ± 0.07a
	D2	35.30 ± 0.19a	54.81 ± 0.24c	4.59 ± 0.01b	1.91 ± 0.16c	10.07 ± 0.01b	16.62 ± 0.08a	28.90 ± 0.09ab	44.48 ± 0.41a	15.06 ± 0.40a
	D3	35.17 ± 0.18a	54.80 ± 0.01c	3.74 ± 0.21c	2.83 ± 0.04a	10.04 ± 0.01b	16.63 ± 0.06a	29.21 ± 0.20a	44.64 ± 0.39a	15.22 ± 0.39a
LJ21	CK	37.68 ± 0.31a	55.34 ± 0.16b	4.52 ± 0.19b	2.35 ± 0.25b	10.10 ± 0.01a	16.68 ± 0.01a	29.03 ± 0.01a	44.46 ± 0.14a	15.41 ± 0.12a
	D1	36.93 ± 0.15b	53.25 ± 0.47c	4.86 ± 0.13ab	2.05 ± 0.12b	10.22 ± 0.12a	16.68 ± 0.03a	29.05 ± 0.03a	45.12 ± 0.28a	15.81 ± 0.40a
	D2	36.47 ± 0.26bc	55.08 ± 0.34b	5.19 ± 0.21a	2.92 ± 0.09a	10.09 ± 0.01a	16.70 ± 0.01a	29.07 ± 0.02a	44.89 ± 0.11a	15.89 ± 0.16a
	D3	36.17 ± 0.04c	56.46 ± 0.31a	5.24 ± 0.13a	3.22 ± 0.16a	10.08 ± 0.05a	16.85 ± 0.13a	28.88 ± 0.10a	44.41 ± 0.32a	15.44 ± 0.14a
SJ18	CK	37.14 ± 0.14a	56.10 ± 0.05b	4.68 ± 0.09b	2.26 ± 0.12b	10.23 ± 0.06a	16.73 ± 0.01a	28.88 ± 0.05b	45.66 ± 0.07a	15.59 ± 0.08b
	D1	37.23 ± 0.23a	56.14 ± 0.03b	5.49 ± 0.14a	3.21 ± 0.09a	10.30 ± 0.04a	16.72 ± 0.09a	28.83 ± 0.04b	45.84 ± 0.12a	16.13 ± 0.06a
	D2	36.80 ± 0.09a	56.17 ± 0.09b	5.39 ± 0.14a	3.15 ± 0.09a	10.21 ± 0.02a	16.78 ± 0.08a	29.06 ± 0.01a	45.73 ± 0.06a	16.08 ± 0.04a
	D3	36.97 ± 0.17a	56.70 ± 0.20a	4.33 ± 0.07b	1.90 ± 0.06c	10.18 ± 0.03a	16.80 ± 0.05a	29.08 ± 0.07a	45.53 ± 0.11a	15.47 ± 0.07b
KJ7	CK	34.97 ± 0.15b	55.39 ± 0.62a	5.71 ± 0.45a	4.07 ± 0.25b	10.17 ± 0.04a	16.84 ± 0.01ab	29.01 ± 0.05a	45.76 ± 0.08ab	16.26 ± 0.21b
	D1	39.37 ± 0.70a	55.95 ± 0.31a	3.50 ± 0.20b	1.03 ± 0.17d	10.17 ± 0.01a	16.62 ± 0.04b	28.99 ± 0.06a	45.26 ± 0.06b	14.79 ± 0.14c
	D2	36.39 ± 0.44b	55.48 ± 0.39a	5.29 ± 0.55a	2.68 ± 0.23c	10.09 ± 0.01a	16.77 ± 0.01ab	28.95 ± 0.02a	45.89 ± 0.09a	16.12 ± 0.35b
	D3	32.88 ± 0.37c	55.57 ± 0.39a	6.23 ± 0.22a	5.13 ± 0.41a	10.05 ± 0.07a	17.08 ± 0.18a	28.83 ± 0.15a	45.64 ± 0.30ab	17.22 ± 0.34a

∑Fa, ∑Fb1, ∑Fb2, and ∑Fb3 represent the relative percentage of Fa, Fb1, Fb2, and Fb3. ACLFa, ACLFb1, ACLFb2, ACLFb3, and ACLAP represent the average chain length of Fa, Fb1, Fb2, Fb3, and amylopectin, respectively.

thereby reducing the grain filling speed, shortening the filling time, and weakening the supply of the source and activity of the sink. An insufficient supply of grain material reduces the total accumulation of grain starch, resulting in a decreased yield [33,34]. In this study, the yield of Kenjing8, Songjing22, and Sonjing18 was less affected by drought, indicating that the drought resistance of the different varieties was different. The yield of the other varieties decreased; however, the decreases were small. This indicates that when the water potential reaches −10 to −40 kPa, the effect on yield is not very significant.

4.2 Effects of water stress on appearance quality

Rice grain quality is complex and includes milling, appearance, nutrition, and taste. Consumers often focus on appearance [35], which is influenced by genetic and environmental factors and is usually evaluated as the percentage of grains with chalkiness [36]. Most studies have shown that water deficiency increased rice chalkiness during the grain-filling stage [15,37,38]. This study confirmed the results of previous studies. At this stage, drought accelerates plant senescence and shortens the filling time, resulting in poor starch filling and subsequently increasing grain chalkiness [19,28]. Compared with the other qualities, the impact of drought stress on chalkiness was the greatest. This is consistent with the conclusion of Lawas et al. [39], who applied combined drought and heat stress to rice during the grain-filling stage. Interestingly, the increase in chalkiness under slight drought (−10 kPa) was higher than that under severe drought (−40 kPa) in the present study. Some studies have suggested that the source–sink relationship had a greater influence on the appearance quality of rice during the late growth period and the lack of a source was the main factor causing an increase in chalkiness [40]. A detailed analysis suggested that slight drought stress reduced photosynthesis, resulting in a serious shortage of sources. With an increase in the degree of drought, plants develop a resistance mechanism to cope with drought and the carbon source in the stem is remobilized. Therefore, the source was increased to a certain extent to alleviate chalkiness.

4.3 Effects of water stress on nutritional quality

Protein, the second component of rice, is a typical quantitative trait. It is susceptible to environmental factors and has relatively low heritability [41]. Some studies have shown that drought treatment increased protein content [42], whereas moderate (−25 kPa) and severe drought (−50 kPa) did not significantly affect protein content [43]. Our study demonstrated that the protein content was significantly reduced in the range of −25 to −40 kPa. The response of protein to water stress is reflected in the protein components. Previous research has found that the content of protein components varied according to variations in genotype, degree and duration of drought, and nitrogen fertilization. Under normal nitrogen application levels, drought stress (−30 kPa) increased the content of total protein, prolamin, and glutelin and had less effect on the globulin content during the filling stage. The effect on albumin content varied from variety to variety [44]. Our study showed that the response of protein components of different varieties to drought was different, and moderate (−25 kPa) and severe drought (−40 kPa) treatments had a greater impact on protein component content. Currently, there are relatively few studies on the effects of drought on protein components and the underlying mechanisms have not been clarified. Therefore, further studies are warranted.

4.4 Effects of water stress on eating and cooking quality

Gel consistency decreases when there is a serious lack of water during the grain-filling stage, resulting in poor taste quality [21]. However, an appropriate water deficit can soften gel consistency and improve rice quality during the filling stage [42,45]. With the aggravation of drought, the rice quality first improves and then gradually deteriorates. In our study, the gel consistency significantly decreased under water stress conditions. We also found that when the soil moisture decreased to −25 to −40 kPa, the comprehensive score of the varieties increased, except for Suijing18, indicating that drought stress did not have a significant negative impact on the taste value in the range of −25 to −40 kPa. While this study was conducted for only 1 year, we selected more varieties than in the past studies. The selected varieties contained different qualities and types, and had large planting areas in Heilongjiang Province. The results are representative and lays a foundation for subsequent research. Irrigation was conducted based on the different characteristics of the varieties to save water and ensure rice yield and quality in agricultural production. Aroma is an important index of rice taste and is mainly affected by 2-acetyl-1-pyrroline [46]. Pandey et al. [15] found that water deficit could reduce the quality but promote the formation of the aroma of Indian basmati rice during the grain-filling stage. However, the mechanism underlying the influence of drought on rice aroma formation requires further exploration.

4.5 Effects of water stress on starch properties

Starch, which accounts for approximately 80% of rice, plays an important role in the eating and cooking quality of rice. The RVA characteristics and amylopectin structure are closely related to taste quality. Rice varieties with a higher percentage of long chains and a lower percentage of short chains of amylopectin have a harder texture [47]. Hu et al. [45] found that mild water stress (−20 kPa) reduced the SBV and increased the PKV and BDV, which improved the eating and cooking quality. Moderate (−40 kPa) and severe drought (−60 kPa) stress reduced PKV, HPV, CPV, and BDV and increased SBV during the filling stage. When the water moisture was −30 kPa, PKV, HPV, CPV, and BDV values of *Japonica* rice significantly increased [48]. The starch structure of grains is altered under drought stress during the filling stage, with irregular shapes, loosely packed, pleated, and less numbered grains [23]. Previous studies mostly used two or three varieties as test materials. In this study, eight *Japonica* rice varieties were used to study the effects of drought on the RVA profile characteristics. Based on this, the amylopectin structure of four varieties with different eating quality responses to drought during the grain-filling stage were analyzed. The results showed that the responses of the RVA profile characteristics and amylopectin structure of the different varieties under drought stress were different. The average chain length of amylopectin was less affected by drought. The RVA values and the proportion of amylopectin chains showed a trend of first increasing and then decreasing or first decreasing and then increasing, indicating that the effects of mild and severe drought on starch were completely different. Starch changes are caused by changes in starch synthesis-related enzymes during the early stages. The study showed that light water stress at different growth stages increased the activities of AGPase, SSS, GBSS, SBE, and DBE. Moderate and severe water stresses had opposite effects [31]. This confirms our findings.

Drought stress limits the formation of starch in the endosperm and changes the pasting properties and structure of starch, which affects the sensory quality [38]. This study only analyzed the response of RVA characteristics and amylopectin structure to drought and lacked a comprehensive analysis of the physicochemical properties and structure of starch (granule morphology, granule size distribution, crystal structure, etc.). Therefore, it is necessary to conduct a systematic analysis to analyze the response of starch to water stress, as well as the interaction and regulation mechanism with rice taste, to provide a reference for the breeding of high-quality varieties and the development of supporting cultivation technologies.

5 Conclusion

The differences in the yield and quality between the varieties were extremely high. Different degrees of water deficit reduced the yield of most varieties and had the greatest negative impact on appearance. Under −25 to −40 kPa, the total protein content and gel consistency were significantly reduced and taste quality was increased. The effects of moderate (−25 kPa) and severe (−40 kPa) water stress on protein components content were higher than those of mild stress (−10 kPa). The protein components and starch content of different varieties responded differently to water stress and mild and severe drought treatments had different effects on starch.

Funding information: This study was supported by the Key Research and Development Program of the Heilongjiang Province (No. GA21B002), the Postdoctoral Surface Fund of Heilongjiang (No. LBH-Z21195), and Scientific Research Start-up Plan for College Learning and Talent Introduction (No. XYB201810).

Author contributions: M.F.: writing – original draft, funding acquisition; T.L., S.S., and M.H.: investigation; C.Y. and C.H.: data curation; H.L. and G.Z: project administration, writing – review and editing.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethical approval: The conducted research is not related to either human or animal use.

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