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Varietal difference in the response of rice chalkiness to temperature during ripening phase across different sowing dates

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Chalkiness, which is highly influenced by high temperature during ripening phase, is one of key factors in determining rice quality and commercial value. This study was conducted to determine varietal differences in chalkiness and in the response of chalkiness to temperature during ripening phase. We evaluated the chalkiness of 42 and 7 varieties with a wide range of genetic background across different sowing dates under field conditions in 2009 and 2010, respectively. Image analysis was used to measure chalky grains and chalkiness was calculated as the percentage of chalky area to projected grain area. A wide range in chalkiness was observed among the tested varieties. These varieties also demonstrated large difference in the response of chalkiness to temperature during ripening phase. Overall, chalkiness was positively correlated with temperature during ripening phase and temperature during second week after heading had the closest correlation with chalkiness. In some varieties such as Dongtingwanxian, Chengnongshuijing, and IR64, their chalkiness was sensitive to temperature and minimum chalkiness could be achieved through optimum sowing date. For these varieties, crop management practice is effective for improving appearance quality. Other varieties such as Yangdao6, Gu154, and Huanghuazhan had low level of chalkiness regardless of sowing dates. These varieties with low and stable chalkiness could be considered as parents in the breeding program for developing new rice varieties with improved appearance quality especially for the future warming environment.

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1. Introduction

Rice is the staple food for more than half of the world's population (Maclean et al., 2002). Increasing grain yield and improving grain quality are equally important for meeting the demands of rice consumers. However, projected increase in global temperature will reduce not only grain yield but also grain quality (Peng et al., 2004; IPCC, 2007; Fitzgerald and Resurreccion, 2009).

Rice quality includes appearance, milling, cooking, eating, and nutritional properties (Koutroubas et al., 2004). Chalkiness of the grains is one of key factors in determining rice quality and commercial value (Yoshioka et al., 2007). Although the preference of rice grain characteristics varies with consumer groups in different countries, translucent kernels without chalkiness are preferred by the majority of rice consumers worldwide (Juliano and Villareal, 1993). Chalkiness is defined as the opaque parts in the endosperm and can be categorized into white-cored, white-belly, milky-white, white-back, and white-based types depending on the site of the chalky part in the grain (Tashiro and Wardlaw, 1991). Appearance quality is largely determined by chalkiness (Lisle et al., 2000). Chalkiness also affects milling quality by reducing grain resistance to forces applied during the milling process, causing grain breakage and consequently a decrease in head rice percentage (Lisle et al., 2000; Counce et al., 2005). This is because chalky endosperms are filled with loosely packed, round and large compound starch granules, while translucent endosperms have tightly packed, polyhedral and small single starch granules (Singh et al., 2006). Wang et al. (2012) reported that the varietal difference in chalkiness explained the difference in head rice percentage among varieties. Furthermore, palatability of the cooked products is reduced by chalkiness because cracks develop readily when chalky grains is steamed or boiled (Cheng et al., 2005). Chalkiness is directly associated with inferior cooking and eating qualities and is a major cause of processing and financial losses (Fitzgerald and Resurreccion, 2009).

The physiological causes of the chalkiness are hypothesized to be an insufficient substrate supply to the developing endosperm, reduced ability to synthesize starch in the endosperm, the degradation of starch by α-amylase during ripening, slower growth

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of starch granules, or different structures of starch that interfere with granular organization (Sato and Inaba, 1976a,b; Yamakawa et al., 2007; Tsukaguchi and Iida, 2008; Fitzgerald and Resurreccion, 2009). Chalkiness is influenced by varieties, environmental conditions, and crop management practices (Tan et al., 2000; Fitzgerald et al., 2009). Rice chalkiness is a complex quantitative trait controlled by polygenes and readily influenced by environment (Tan et al., 2000). Several QTLs have been found to control the chalkiness of rice grains (Tan et al., 2000; Guo et al., 2011). Varietal differences in chalkiness were reported in several studies (Wang et al., 2006; Yamakawa et al., 2007; Ambardekar et al., 2011). Among environmental factors, temperature has the largest influence on chalkiness (Cheng and Zhong, 2001). Formation of chalky grains is greatly enhanced by high temperature during ripening phase (Tashiro and Wardlaw, 1991; Yamakawa et al., 2007), which is recently occurring more frequently due to global warming (Wakamatsu et al., 2007). Therefore, grain chalkiness caused by high temperature stress will become a global problem for rice production in the near future (Ishimaru et al., 2009). Recent research has shown that elevated nighttime temperature increased chalkiness (Fitzgerald and Resurreccion, 2009; Ambardekar et al., 2011). Unfavorably warm weather during the grain filling period results in reduced enzymatic activity related to grain filling, increased respiratory consumption of assimilation products, disturbed water balance, decreased sink activity of glumous flowers, and increased loosely-packed starch granules (Inaba and Sato, 1976; Sato and Inaba, 1976a,b; Tashiro and Wardlaw, 1991). Chalkiness is also affected by crop management practices such as nitrogen fertilization (Qiao et al., 2011) and water management (Hayashi et al., 2011).

Many studies have been conducted about the chalkiness of rice grains. However, most of them were carried out for understanding the physiological and genetic mechanism underlying the chalky formation under normal or high temperature (Tan et al., 2000; Yamakawa et al., 2007; Fitzgerald and Resurreccion, 2009; Zhang et al., 2009; Zhou et al., 2009). These studies were often conducted under controlled-environment conditions with a few varieties. In this study, we evaluated the chalkiness of 42 and 7 varieties with a wide range of genetic background across different sowing dates under field conditions in 2009 and 2010, respectively. The objectives were to determine varietal differences in chalkiness and in the response of chalkiness to temperature during ripening phase and to determine which stage of grain filling was most sensitive to temperature for chalky formation.

2. Materials and methods

Field experiments were conducted in Dajin Township (29°51′ N, 115°53′ E), Wuxue County, Hubei Province, China, during the rice-growing season from May to October in 2009 and 2010. Soil in the field for 2009 experiment has the following properties: pH 5.01, 30.1 g kg^{-1} organic matter, 1.39 g kg^{-1} total N, 5.92 mg kg^{-1} available P, and 46.3 mg kg^{-1} available K. Soil in the field for 2010 experiment has the following properties: pH 5.70, 21.9 g kg^{-1} organic matter, 1.77 g kg^{-1} total N, 8.75 mg kg^{-1} available P, and 66.1 mg kg^{-1} available K. Monthly mean temperature from May to October were 22.5, 28.5, 30.0, 29.5, 25.8, 21.0 °C in 2009, and were 22.2, 25.2, 29.3, 30.1, 25.0, 17.7 °C in 2010, respectively.

In 2009, four sowing dates were used and 42 varieties were arranged in three replications within each sowing date. In 2010, six sowing dates were used and seven varieties were arranged in three replications within each sowing date. Sowing dates were May 5, May 16, May 26, and June 4 in 2009, and April 27, May 7, May 15, May 26, June 6, and June 15 in 2010. Forty-two varieties used in 2009 were from rice core collection. Among the 42 varieties, 12 varieties were japonica and the rest were indica. Most varieties were from China except for IR64, IR661-1, and Gu154 (from IRRI with original name of IR837-36-1), IRAT109 (from IITA), and Gui630 (from Gunaya). Based on the varietal difference in the response of chalkiness to temperature in 2009, seven varieties were selected for the 2010 experiment. Another selection criterion was the similarity in growth duration among the varieties. The seven varieties were indica, and five of them were from China and two from IRRI.

Seedlings were raised in wet seedbed in both years. Seedlings were transplanted with a hill spacing of 0.133 m × 0.267 m and with 2–3 seedlings per hill. Seedling age was 20–25 days in 2009 and 25–33 days in 2010. Seedling age was variable across the sowing dates in order to reduce the differences in seedling size at transplanting. Phosphorus in the form of calcium superphosphate (40 kg P ha^{-1}) and zinc in the form of zinc sulfate heptahydrate (5 kg Zn ha^{-1}) were applied and incorporated in the field 1 day before transplanting. Potassium in the form of potassium chloride (100 kg K ha^{-1}) was split equally at basal and panicle initiation. Nitrogen in the form of urea (150 kg N ha^{-1}) was split-applied: 40% at basal, 30% at mid-tillering, and 30% at panicle initiation in 2009. Total N rate was 135 kg ha^{-1} with the split application of 50% at basal, 20% at mid-tillering, and 30% at panicle initiation in 2010. The field was kept 5–10 cm water depth from 3 days after transplanting to 7 days before maturity. Pests, diseases, birds, and weeds were intensively controlled for avoiding yield losses. Other crop management practices followed the local recommendation to achieve high grain yield.

Plant samples were taken from each plot at crop maturity for the measurements of various traits. Grains were threshed and filled grains were separated from unfilled grains and debris using an air blower. Two subsamples of air-dried and filled grain each at 26 g were taken from each plot for the measurement of chalkiness. Rough rice was de-husked using a husker (SY88-TH, BRIC, Korea). From each subsample, 10 g brown rice was taken for milling using a Miller (Pearlest, Kett, Japan), and then head rice was divided from broken rice using a separator (JFQS-13*20, China). Chalkiness was evaluated following the method of Yoshioka et al. (2007) with some modification. A digital image was created by placing all head rice of each subsample on the scanner (Epson Expression 1680 Professional, Epson, America) with a white fraction back board, which increased the contrast between chalky and translucent parts in the images. Digital images were analyzed using an image analyzing software (Image J, the National Institutes of Health, USA). With the tool of “Threshold Color” in the software, we determined two threshold values of brightness pass in hue-saturation-brightness color model to separate chalky, translucent and background parts. Then the areas of pixel in chalky and translucent parts were measured, and chalkiness was calculated as the percentage of chalky area to projected grain area.

Air temperature was obtained from the temperature data loggers (HOBO H08-032-08, Onset Computer Corp., USA). Daily mean temperature was calculated as the average of daily minimum and maximum temperature. Correlation analysis was done to determine the relationship between chalkiness and average daily mean temperature during different periods of ripening phase.

3. Results

Air temperature during rice growing seasons in 2009 and 2010 followed normal pattern which increased from May to June, reached a peak in July and August, and declined from September to October (Fig. 1). Monthly mean temperature in June and October was greater in 2009 than in 2010. The difference in temperature between the two years was relatively small in May, July, August, and September. In general, 2010 was cooler than 2009. Heading dates

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