Effects of Lodging at Different Filling Stages on Rice Yield and Grain Quality

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Abstract: The effects of lodging of rice plants from 20 d after full heading to maturity on yield and grain quality were investigated with a hybrid rice combination Liangyoupeijiu and a japonica rice cultivar CY-6. The results showed that, except for brown rice rate, almost all parameters for yield and grain quality including ratio of grain length to grain width, gelatinization temperature and gel consistency, were significantly influenced by lodging and thus deteriorated. Regression analysis suggested that, lodging one day earlier at the grain-filling stage could cause 2.66% to 2.71% of yield loss, 1.8 to 2.6 percentage points decrease of seed-setting rate, 0.26 to 0.32 g reduction of 1000-grain weight, 0.097 to 0.155 percentage point decline of milled rice rate, as well as 0.13 to 0.27 percentage point increase of chalky grain rate, and 0.021 to 0.024 percentage point rise of protein content, and subsequently lower the eating quality.

Key words: rice; lodging; filling stage; yield; grain quality

Lodging has been one of the important constraints on rice production for a long time. When lodging occurs, the canopy structure would be destroyed, and the capacity of photosynthetic rate and dry matter production sharply reduced (Setter et al, 1997). In severe cases, it breaks stems or pulls the roots out, blocking the transportation of water, minerals and photosynthate, leading to a substantial decline in yield and quality (Hitaka, 1969; Kashiwagi et al, 2005). In recent years, as high-yielding rice cultivars characterized by large panicle, as well as simplified planting techniques such as direct-seeding and seedling broadcasting, are widely applied, the potential risk of lodging is increasing. In light of this, more and more attention has been paid to it, and many findings such as the causes for lodging, lodging damage mechanism, the prevention of lodging have been reported (Zhang et al, 1999; Wan and Ma, 2003; Xiao et al, 2005; Zhang et al, 2005; Li H J et al, 2009). However, the effects of lodging time, which is always uncertain for its concern with irregular severe weather or pests and diseases, are still rarely studied so far. According to this situation, this study was undertaken to analyze the relationships among lodging times, rice yield and grain quality with a hybrid rice combination and an inbred japonica rice cultivar, which were treated with lodging at different grain-filling stages, so as to assess lodging impacts accurately.

MATERIALS AND METHODS

Rice materials and experimental design

The experiments were carried out at the experimental farm of Yangzhou University (32.23° N), China, in 2007 and 2008, with sandy loam soil. The seeds of a two-line hybrid rice Liangyoupeijiu and an inbred japonica rice CY-6, were sown on 10 May, and then seedlings were transplanted manually to paddy fields on 10 June. A randomized complete block design with three replications was applied. Each plot was 3.0 m wide and 3.4 m long, with a 20-cm row spacing and a 17-cm plant spacing, and each hill contained one Liangyoupeijiu seedling or two CY-6 seedlings. During the growth duration, the field was fertilized with 450 kg/hm² urea by a ratio of basal : tillering : panicle = 3 : 3 : 4. At 20 d after full heading, an alternating wet and dry irrigation strategy was used; besides, other conventional managements in Jiangsu Province were adopted. At 20 d, 30 d and 40 d after full heading, 60 hills of rice plants in each plot were chosen to be pressed continuously with a bamboo pole to induce a 30°–60° tilt angle of plants within 3 d, till ultimately lodged. The plants that normally matured without lodging were served as control. In 2008, there were nine rainy days at the rice grain-filling stage, accounting for less than 1/5 of total period, and the rest were all sunny or cloudy days.

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Measuring items and methods

At the harvest stage (all grains became yellow), 20 hills of rice plants in each plot were chosen based on the average panicle number of the plot to determine the yield and its components with standard measuring methods, and the rest plants were harvested to analyze grain quality.

The harvested and cleaned grains were then stored at room temperature for three months before determination of grain quality traits. Milling, appearance, cooking and eating qualities were measured according to the standard ‘NY/T83-1988’ (Ministry of Agriculture of People’s Republic of China, 1998); amylose and crude protein contents were determined by a rapid near-infrared grain quality analyzer (Foss Tecator, Sweden) (Sun et al., 2006); starch viscosity characteristics were determined by a rapid visco analyzer (type Super 3, Newport Scientific) (Zhang et al., 2009).

Data were statistically analyzed with SAS6.12 (SAS Institute, USA). Because the trends of trials in the two years are basically consistent, the results of year 2008 are mainly reported.

RESULTS

Grain yield and its components

There were sharp declines for rice yields after lodging in the both materials. For Liangyoupeijiu, the yields in lodging treatments at 40, 30 and 20 d after full heading (DAFH) decreased by 30.0%, 64.2% and 83.9%, respectively, compared with the control; For CY-6, the yields decreased by 4.9%, 40.7% and 61.4%, respectively (Table 1). It is revealed that the influence of lodging on the yield is enormous, the earlier the lodging occurred, the greater the yield loss. Yield component analysis depicted that the decline of yield was mainly caused by the reduction of seed-setting rate and 1000-grain weight, and the former had greater impact on yield than the later, for it decreased more rapidly. Panicle number per unit area and grain number per panicle were determined before lodging, therefore, they had little effects on yields.

Milling quality

Lodging at the grain-filling stage had no significant effects on the brown rice rate (Table 2), but the milled rice rate were evidently lower in lodging treatments compared to the control, and the earlier the lodging occurred, the greater the decline was. For Liangyoupeijiu, the milled rice rate in lodging treatment at 20 DAFH was 5.1 percentage points lower than the control. So was the head milled rice rate, and the only difference was the head milled rice rate declined more when lodging happened.

Grain appearance quality

Table 3 showed that there were no significant differences in the traits of grain length, grain width and ratio of length to width among all the treatments (except for the grain length in Liangyoupeijiu) in the two tested materials. The results also indicated the earlier the lodging occurred, the higher the chalky grain rate and chalkiness degree were. Nevertheless, the fluctuations of chalky grain rate and chalkiness degree for all the treatments in the two materials were observed along with lodging times. For example, the

### Table 1. Yield and yield components.

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment time</th>
<th>Panicle number per hm² (×10⁴)</th>
<th>Grain number per panicle</th>
<th>Seed-setting rate (%)</th>
<th>1000-grain weight (g)</th>
<th>Yield (kg/hm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liangyoupeijiu</td>
<td>20 DAFH</td>
<td>209.8 a</td>
<td>229.2 a</td>
<td>20.2 d</td>
<td>18.0 d</td>
<td>1 741.4 d</td>
</tr>
<tr>
<td></td>
<td>30 DAFH</td>
<td>211.2 a</td>
<td>223.7 a</td>
<td>36.6 c</td>
<td>22.3 c</td>
<td>3 860.5 c</td>
</tr>
<tr>
<td></td>
<td>40 DAFH</td>
<td>210.2 a</td>
<td>212.4 a</td>
<td>66.5 b</td>
<td>25.5 b</td>
<td>7 555.1 b</td>
</tr>
<tr>
<td></td>
<td>NM (CK)</td>
<td>209.4 a</td>
<td>219.5 a</td>
<td>87.4 a</td>
<td>26.9 a</td>
<td>10 796.0 a</td>
</tr>
<tr>
<td>CY-6</td>
<td>20 DAFH</td>
<td>337.1 a</td>
<td>100.8 a</td>
<td>50.4 c</td>
<td>16.7 d</td>
<td>2 854.6 c</td>
</tr>
<tr>
<td></td>
<td>30 DAFH</td>
<td>338.4 a</td>
<td>101.3 a</td>
<td>68.8 b</td>
<td>18.6 c</td>
<td>4 388.9 b</td>
</tr>
<tr>
<td></td>
<td>40 DAFH</td>
<td>347.6 a</td>
<td>98.4 a</td>
<td>89.8 a</td>
<td>22.9 b</td>
<td>7 035.7 a</td>
</tr>
<tr>
<td></td>
<td>NM (CK)</td>
<td>335.1 a</td>
<td>99.2 a</td>
<td>92.4 a</td>
<td>24.1 a</td>
<td>7 397.8 a</td>
</tr>
</tbody>
</table>

| 20 DAFH, 30 DAFH and 40 DAFH stand for lodging at 20 d, 30 d and 40 d after full heading, respectively; NM, Natural maturation. Data followed by the common letter within the same column indicate no significant difference at P < 0.05 level.

### Table 2. Effects of lodging on milling quality of rice.

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment time</th>
<th>Brown rice rate (%)</th>
<th>Milled rice rate (%)</th>
<th>Head milled rice rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liangyoupeijiu</td>
<td>20 DAFH</td>
<td>78.6 a</td>
<td>65.2 c</td>
<td>44.2 c</td>
</tr>
<tr>
<td></td>
<td>30 DAFH</td>
<td>78.6 a</td>
<td>66.7 bc</td>
<td>47.9 b</td>
</tr>
<tr>
<td></td>
<td>40 DAFH</td>
<td>78.9 a</td>
<td>68.0 b</td>
<td>49.5 ab</td>
</tr>
<tr>
<td></td>
<td>NM (CK)</td>
<td>79.8 a</td>
<td>70.3 a</td>
<td>51.8 a</td>
</tr>
<tr>
<td>CY-6</td>
<td>20 DAFH</td>
<td>84.3 a</td>
<td>73.9 b</td>
<td>68.6 c</td>
</tr>
<tr>
<td></td>
<td>30 DAFH</td>
<td>84.3 a</td>
<td>75.1 ab</td>
<td>71.0 b</td>
</tr>
<tr>
<td></td>
<td>40 DAFH</td>
<td>83.9 a</td>
<td>75.5 ab</td>
<td>72.6 ab</td>
</tr>
<tr>
<td></td>
<td>NM (CK)</td>
<td>84.1 a</td>
<td>76.5 a</td>
<td>73.6 a</td>
</tr>
</tbody>
</table>

| 20 DAFH, 30 DAFH and 40 DAFH stand for lodging at 20 d, 30 d and 40 d after full heading, respectively; NM, Natural maturation. Data followed by the common letter within the same column indicate no significant difference at P < 0.05 level.
chalky grain rates at 40, 30 and 20 DAFH in Liangyoupeijiu were 3.1, 5.9 and 8.6 percentage points higher than the control, respectively, comparing with 1.1, 2.1 and 3.4 percentage points in CY-6. This suggests that chalky grain rate and chalkiness degree grain might be more sensitive to lodging in cultivars with high chalky grain rate.

**Protein content**

As shown in Fig. 1, the later the lodging occurred, the lower the protein content was, which agreed with the results of Zhang et al (2002). The possible reason is that the accumulating speed of amylum might be faster than that of protein. There was no significant difference between two adjacent treatments, even for the firstly lodged treatments of 20 DAFH in the two materials, the protein contents were only 0.5 and 0.8 percentage point higher than that of the control. For later lodged treatments such as 40 DAFH, the protein contents were almost equal to the control.

**Cooking and eating quality**

Effects of lodging on rice amylose content can be summarized as that, the amylose content decreased with the delay of lodging (Fig. 2-A), which supported the conclusions of Zhong and Cheng (2003). There were differences in the decline range between the two materials. In Liangyoupeijiu, the amylose content of 20 DAFH was the highest, reaching 27.05%, but in the following treatments, the decline ranges between any two adjacent lodging treatments were very small; whereas in CY-6, the amylose contents of all the treatments ranged from 17.20% to 17.75%, with no significant difference.

Gelatinization temperatures of the treatments in the two materials varied within a narrow range from 71.7 °C to 73.0 °C with no significant differences. It suggests that lodging at the full heading had no obvious effect on gelatinization temperature of rice (Fig. 2-B).

### Table 3. Effects of lodging on appearance quality of rice.

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment time</th>
<th>Grain length (mm)</th>
<th>Grain width (mm)</th>
<th>Ratio of length to width</th>
<th>Chalky grain rate (%)</th>
<th>Chalkiness degree (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liangyoupeijiu</td>
<td>20 DAFH</td>
<td>6.85 ab</td>
<td>2.41 a</td>
<td>2.84 a</td>
<td>40.5 a</td>
<td>14.6 a</td>
</tr>
<tr>
<td></td>
<td>30 DAFH</td>
<td>7.12 a</td>
<td>2.47 a</td>
<td>2.88 a</td>
<td>37.8 ab</td>
<td>14.2 b</td>
</tr>
<tr>
<td></td>
<td>40 DAFH</td>
<td>6.66 b</td>
<td>2.40 a</td>
<td>2.78 a</td>
<td>35.0 b</td>
<td>13.4 c</td>
</tr>
<tr>
<td></td>
<td>NM (CK)</td>
<td>6.70 b</td>
<td>2.38 a</td>
<td>2.82 a</td>
<td>31.0 c</td>
<td>12.7 d</td>
</tr>
<tr>
<td>CY-6</td>
<td>20 DAFH</td>
<td>5.79 a</td>
<td>2.78 a</td>
<td>2.09 a</td>
<td>16.8 a</td>
<td>8.6 a</td>
</tr>
<tr>
<td></td>
<td>30 DAFH</td>
<td>5.75 a</td>
<td>2.77 a</td>
<td>2.06 a</td>
<td>15.5 ab</td>
<td>8.0 b</td>
</tr>
<tr>
<td></td>
<td>40 DAFH</td>
<td>5.76 a</td>
<td>2.76 a</td>
<td>2.09 a</td>
<td>14.5 bc</td>
<td>7.6 b</td>
</tr>
<tr>
<td></td>
<td>NM (CK)</td>
<td>5.69 a</td>
<td>2.73 a</td>
<td>2.09 a</td>
<td>13.4 c</td>
<td>6.9 c</td>
</tr>
</tbody>
</table>

20 DAFH, 30 DAFH and 40 DAFH stand for lodging at 20 d, 30 d and 40 d after full heading, respectively; NM, Natural maturation. Data followed by the common letter within the same column indicate no significant difference at $P < 0.05$ level.

![Fig. 1. Effects of lodging on protein content of rice.](image1)

![Fig. 2. Effects of lodging on eating and cooking quality of rice.](image2)
Thus, the effect of breakdown of starch, as well as lower setback, lead to normal circumstances, higher peak viscosity and important indicators of eating quality of rice, under to the existent findings, starch RVA properties are lodging in CY-6, but not in Liangyoupeijiu. According to the results in the two materials, but no significant difference was observed in the treatments of Liangyoupeijiu were close to the control (59.5 mm), which was 4.4 mm longer than that at the 20 DAFH treatment; and in CY-6, the gel consistency varied with the rice materials. In Liangyoupeijiu, the gel consistency increased significantly to increase with the delay of lodging. The peak times of the treatments in Liangyoupeijiu were close to the control, whereas in CY-6, they were significantly longer than the control (Table 4).

The breakdown value tended to rise with the delay of lodging in the two materials, but no significant difference was observed in the treatments of Liangyoupeijiu. Setback value decreased with the delay of lodging in CY-6, but not in Liangyoupeijiu. According to the existed findings, starch RVA properties are important indicators of eating quality of rice, under normal circumstances, higher peak viscosity and breakdown of starch, as well as lower setback, lead to good taste (Li G et al, 2009). Thus, the effect of lodging on eating quality can be described as the earlier the lodging, the worse the taste.

RVA characteristics of rice starch

In RVA characteristics of rice starch, the peak viscosity, hot paste viscosity and final viscosity tended to increase with the delay of lodging. The peak times for the treatments in Liangyoupeijiu were close to the control, whereas in CY-6, they were significantly longer than the control (Table 4).

Table 5. Equations between lodging stages and parameters of yield and grain quality.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation for Liangyoupeijiu</th>
<th>Equation for CY-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed-setting rate</td>
<td>$y = 2.146x - 23.7950, R^2 = 0.9856^{**}$</td>
<td>$y = 1.823x + 14.2680, R^2 = 0.9903^{**}$</td>
</tr>
<tr>
<td>1000-grain weight</td>
<td>$y = 0.2740x + 13.4150, R^2 = 0.9291^{*}$</td>
<td>$y = 0.3209x + 9.8251, R^2 = 0.9724^{**}$</td>
</tr>
<tr>
<td>Yield</td>
<td>$y = 286.9x - 432.5, R^2 = 0.9913^{**}$</td>
<td>$y = 200.3x - 129.1, R^2 = 0.9829^{**}$</td>
</tr>
<tr>
<td>Milled rice rate</td>
<td>$y = 0.1550x + 62.0270, R^2 = 0.9946^{**}$</td>
<td>$y = 0.0965x + 72.0159, R^2 = 0.9320^{**}$</td>
</tr>
<tr>
<td>Head milled rice rate</td>
<td>$y = 0.2253x + 40.3220, R^2 = 0.9603^{**}$</td>
<td>$y = 0.2024x + 64.6859, R^2 = 0.9938^{**}$</td>
</tr>
<tr>
<td>Chalky grain rate</td>
<td>$y = -0.2657x + 45.7640, R^2 = 0.9993^{**}$</td>
<td>$y = -0.1329x + 19.5006, R^2 = 0.9737^{**}$</td>
</tr>
<tr>
<td>Chalkiness degree</td>
<td>$y = -0.0605x + 15.8800, R^2 = 0.9875^{**}$</td>
<td>$y = -0.0641x + 9.9231, R^2 = 0.9340^{**}$</td>
</tr>
<tr>
<td>Protein content</td>
<td>$y = -0.0242x + 9.4604, R^2 = 0.9945^{**}$</td>
<td>$y = -0.0210x + 7.9148, R^2 = 0.9140^{**}$</td>
</tr>
<tr>
<td>Amylose content</td>
<td>$y = -0.0775x + 28.2220, R^2 = 0.8893$</td>
<td>$y = -0.0202x + 18.1258, R^2 = 0.9110^{**}$</td>
</tr>
<tr>
<td>Gelatinization temperature</td>
<td>$y = -0.0235x + 73.0980, R^2 = 0.7059$</td>
<td>$y = -0.0379x + 73.822, R^2 = 0.7244$</td>
</tr>
<tr>
<td>Gel consistency</td>
<td>$y = 0.1444x + 51.8820, R^2 = 0.9694^{*}$</td>
<td>$y = 0.0467x + 78.5360, R^2 = 0.2112$</td>
</tr>
<tr>
<td>Peak viscosity</td>
<td>$y = 1.3724x + 209.1800, R^2 = 0.8509$</td>
<td>$y = 0.9072x + 253.0086, R^2 = 0.9832^{**}$</td>
</tr>
<tr>
<td>Breakdown</td>
<td>$y = -0.3801x + 65.5640, R^2 = 0.1527$</td>
<td>$y = 0.5277x + 77.6732, R^2 = 0.8991$</td>
</tr>
<tr>
<td>Setback</td>
<td>$y = -0.7701x + 79.4110, R^2 = 0.3398$</td>
<td>$y = -0.7637x + 34.8836, R^2 = 0.9888^{**}$</td>
</tr>
</tbody>
</table>

* and **, Significant correlation at $P < 0.05$ and $P < 0.01$ levels, respectively.

Fig. 2-C illustrated that the effects of lodging on gel consistency varied with the rice materials. In Liangyoupeijiu, the gel consistency increased significantly as lodging delayed, the longest rice glue was observed in the control (59.5 mm), which was 4.4 mm longer than that at the 20 DAFH treatment; and in CY-6, the gel consistency ranged from 79.3 to 81.4 mm, and no significance was observed.

**DISCUSSION**

It is repeatedly verified and reported that lodging during grain-filling period may reduce yield and
quality of rice, but because of the different lodging stages previous researchers have studied, the quantitative and consistent findings on impacts of lodging are still scarce.

The results of this study also showed that lodging had great impact on yield of rice. For Liangyoupeijiu and CY-6, if lodging occurred at the medium stage of grain-filling period (i.e., 27 d and 22 d after full heading), only 30.6% and 42.1% of normal yield would be produced respectively, even if the lodging happened one week before harvest, the yield might be less than 85% of normal rice. In addition, the impacts of lodging on rice quality are comprehensive, for almost all the quality traits of rice would be reduced if lodging occurred. Therefore, it is very important to prevent lodging, so as to obtain high yield and good quality in rice.

The results also showed that the impacts of lodging on yield and quality varied with rice materials. For the mid-mature japonica rice CY-6, the average yield ratio of the lodging treatments to the normal ones was about 10 percentage points higher than that of the same treatments for Liangyoupeijiu, and the quality traits such as the chalky grain rate, head milled rice rate and amylose content were also better than Liangyoupeijiu. Therefore, in regions where lodging happens frequently, favorable cultivars such as CY-6 are recommended to avoid negative effects of lodging. In addition, according to the fact that almost all the quality traits at 40 DAFH, or even at 30 DAFH in CY-6 were close to the normally matured rice, it is feasible for grains from late lodged plants of some rice cultivars to be used as food, rather than forage or industrial materials.

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