Yield and Lodging Resistance of ‘Tachiayaka’, a Novel Rice Cultivar with Short Panicles for Whole-Crop Silage

Kei Matsushita¹,², Takuro Ishii¹, Osamu Ideta¹, Shuichi Iida¹, Yoshihiro Sunohara¹, Hideo Maeda¹ and Hajime Watanabe²

¹National Agriculture and Food Research Organization (NARO), Western Region Agricultural Research Center, Hiroshima 721-8514, Japan; ²Graduate School of Science & Technology, Niigata University, Niigata 950-2181, Japan

Abstract: ‘Tachiayaka’ is a novel cultivar of rice (Oryza sativa L.) with short panicles that is suitable for use in whole-crop silage. It was selected from bulked progeny obtained from two backcrosses of ‘Hoshiaoba’ to F₁ plants of ‘Chugoku 146’ (‘Hoshiaoba’) × ‘Gokutansui (00kosen11)’. The unhulled rice yield of ‘Tachiayaka’ was comparable to that of ‘Tachisuzuka’, a short-panicle cultivar with high digestibility in cattle, in multi-location trials over a wide area spanning the Hokuriku to Chugoku regions in Japan. The whole-crop yield and the maturity of ‘Tachiayaka’ were comparable to those of ‘Hoshiaoba’. These findings indicated the suitability of ‘Tachiayaka’ for cultivation across a wide area of Japan. The characters associated with lodging resistance in ‘Tachiayaka’, including lodging index, were superior to those of ‘Hoshiaoba’. The high lodging resistance of ‘Tachiayaka’ will enable its cultivation in regions where lodging occurs frequently.

Key words: Cultivar, Lodging resistance, Rice, Short-panicle, ‘Tachiayaka’, Whole-crop silage.

In Japan, the cultivation of rice (Oryza sativa L.) for use in whole-crop silage (WCS) has been encouraged by the government during the last decade. As a result, more than 20,000 ha of rice are now grown for WCS. In WCS, the whole rice plant, including panicles, leaves, and stems, is harvested at the yellow ripening stage, conditioned into silage, and then fed to cattle. Several cultivars for WCS use have been released. However, there is loss of the nutrients because some of the grain eaten by cattle is excreted in feces without being digested (Yamamoto et al., 2005; Fang et al., 2011). As a solution to this problem, a new rice cultivar with short panicles, ‘Tachisuzuka’, was developed and released (Matsushita et al., 2011). The short panicles resulted in a markedly low grain/straw ratio, and the milk yield in lactating cattle fed ‘Tachisuzuka’ silage increased (Kouno, 2011).

Commercial cultivation of ‘Tachisuzuka’ for WCS is already underway in warmer regions of Japan. However, because of its late maturity, cultivation of ‘Tachisuzuka’ in colder areas of Japan risks insufficient ripening. For example, ‘Tachisuzuka’ often remains immature in the Hokuriku region (Goto et al., 2012). Additionally, the monoculture causes a concentration of labor at harvest time. Thus, a rice cultivar for WCS with short panicles and earlier maturity than that of ‘Tachisuzuka’ is needed.

We report the breeding process of a novel cultivar, ‘Tachiayaka’, with short panicles and earlier maturity. We also addressed the potentially wide adaptability of ‘Tachiayaka’, based on grain and whole-crop yields in trials at the breeding site and in a multi-location trial that covered a wide area from the Hokuriku to Chugoku regions in Japan. The adaptability of ‘Tachiayaka’ to cultivation via direct seeding in flooded paddy fields as well as via conventional transplanting is reported and its yield and lodging resistance characteristics are analyzed in detail.
### Materials and Methods

1. **Breeding process**

   An outline of the procedure used to breed ‘Tachiayaka’ is shown in Table 1. The parental line ‘Gokutsansui (00kosen11)’ was a short-panicled spontaneous mutant obtained from the F₁ population of a cross between ‘Aoinokaze’ and ‘Chugoku 156’ (Fig. 1). It was chosen as a parental line to breed a cultivar with low grain yield. To introduce this short-panicle mutation into rice lines for WCS use, we crossed ‘Chugoku 146’ (‘Hoshiaoba’) and ‘Gokutsansui (00kosen11)’ in 2001 (Cross 1). ‘Hoshiaoba’ is a major WCS cultivar in Japan that has high grain and straw yields (Sakai et al., 2003). The two backcrosses, ‘Hoshiaoba’ × Cross 1 F₁ progeny (Cross 2) and ‘Hoshiaoba’ × Cross 2 BC₁F₁ progeny (Cross 3), were conducted in 2003 and 2004. The bulked progeny were cultivated in the winters of 2004/2005 (BC₂F₁) and 2005 (BC₂F₂). The BC₂F₃ population was subjected to individual selection in 2005. Forty-seven selected plants showed panicle morphology similar to that of ‘Gokutsansui (00kosen11)’. Progeny of the BC₂F₃ plants were selected according to the pedigree method (Yamamoto et al., 1996). The preliminary yield trials were carried out in 2008, and multi-location trials were carried out from 2009 – 2011. In 2010, one promising breeding line was designated as ‘Chugoku-shi 205’. In 2012, we submitted an application to the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) for official registration under the name ‘Tachiayaka’.

2. **Multi-location trials and direct seeding test**

   Breeder’s seeds of three rice cultivars, ‘Tachiayaka’, ‘Hoshiaoba’, and ‘Tachisuzuka’, were used. ‘Hoshiaoba’ was selected as the control variety, and the short-panicled ‘Tachisuzuka’ was used as a reference for several agronomical traits during trials in Fukuyama. A total of 11 trials were carried out at three locations in Japan: National Agriculture and Food Research Organization (NARO)/ Agricultural Research Center (ARC), Joetsu, Niigata (37°12′ N, 138°27′ E); National Institute of Crop Science (NICS), Tsukubamirai, Ibaraki (36°01′ N, 140°02′ E); and

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**Table 1. Outline of breeding procedure of the ‘Tachiayaka’ rice cultivar.**

| Year      | Generation | Breeding experiments                                      | Name of selected line |
|-----------|------------|----------------------------------------------------------|-----------------------|
| 2001      | (Cross 1)  | Chugoku 146 × Gokutsui (00kosen11)                       | 07 Takeisen 55        |
| 2003      | (Cross 2)  | Hoshiaoba × F₁ (from Cross 1)                            | 08 Tayo 4             |
| 2004      | (Cross 3)  | BC₂F₁ (from Cross 2) × Hoshiaoba                        | Tashukei 1088         |
| 2004/2005 | BC₂F₁     | Generation advancement (during winter, in greenhouse)   |                       |
| 2005      | BC₂F₂     | Generation advancement                                   |                       |
| 2006      | BC₂F₃     | Individual selection (47 of 4000 plants selected)        |                       |
| 2007      | BC₂F₄     | Selection of individual lines (2 of 47 lines selected)   |                       |
| 2008      | BC₂F₅     | Preliminary yielding trial                               |                       |
| 2009      | BC₂F₆     | Multi-location trials                                    |                       |
| 2010 – 2011| BC₂F₇     | Multi-location trials                                   | Chugoku-shi 205       |
| 2012      | BC₂F₈     | Registration by MAFF                                      |                       |
| 2012      | BC₂F₉     | Registration by MAFF                                      | Tachiayaka             |

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**Fig. 1.** Genealogy of ‘Tachiayaka’.

‘Tashukei 174’: ‘Sweon 258’/‘Ohseto’/‘Chugoku 69’.

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*“Tashukei 174”: ‘Sweon 258’/‘Ohseto’/‘Chugoku 69’.*
of flooded paddy fields. At the yellow ripening stage or maturing stage, samples from 1.0 – 3.2 m
were harvested to measure the whole-crop and unhulled rice dry matter. In the trials at Joetsu and
Tsukubamirai in 2011, dry matter was estimated from air-dried weight (Dry matter = Air-dried
weight × 0.85), and unhulled rice weight was estimated from brown rice weight (Unhulled rice weight = Brown rice weight × 1.2). One-way analysis of variance (ANOVA) and Tukey-Kramer’s honestly significantly different (HSD) test were employed for statistical analysis. Location and cultivar were treated as factors and year as replication.

Fig. 2. Monthly mean temperatures, solar radiation, and monthly rainfalls during the 2009 – 2011 cropping seasons at Joetsu, Tsukubamirai, and Fukuyama.

Table 2. Outline of yielding trials in multi-location and direct seeding tests.

| Cultivation method | Location     | Year          | Date of seeding | Date of transplanting | Date of top dressing | Planting density (m⁻²) | Basal dressing (g m⁻²) | Top dressing (g m⁻²) |
|--------------------|--------------|---------------|-----------------|-----------------------|----------------------|------------------------|-----------------------|-----------------------|
| Transplanting      | Joetsu       | 2009 – 2011   | 18 – 22 April   | 19 – 20 May           | 20 – 22 July         | 18.5                   | N 6.0 6.0 6.0          | 3.0 0.0 4.1           |
|                    | Tsukubamirai | 2010 – 2011   | 21 – 23 April   | 17 – 18 May           | 22 – 23 July         | 22.2                   | N 16.0 16.0 16.0       | 0.0 0.0 0.0           |
|                    | Fukuyama     | 2009 – 2011   | 6 – 9 May       | 9 – 12 June           | 22 – 31 July         | 20.8                   | N 16.8 16.8 16.8       | 3.4 0.0 3.4           |
| Direct seeding     | Fukuyama     | 2009 – 2011   | 13 – 21 May     | —                     | 22 July              | 120                    | N 11.2 11.2 11.2       | 3.4 0.0 3.4           |

1) Hills m⁻² for transplanting and seeds m⁻² for direct seeding.

NARO/Western Agricultural Research Center (WARC), Fukuyama, Hiroshima (34°30′N, 133°23′E). Data for mean temperature, solar radiation, and rainfall were provided by each institution (Fig. 2). Cultivation methods, including planting density, fertilization, water management, and weed control, and study design followed the standards for rice yield trials at each institution (Table 2). Two replicate trials were performed at Fukuyama, while one trial each was conducted at Joetsu and Tsukubamirai. All transplanting trials used three seedlings per hill. The direct seeding test was carried out at NARO/WARC by directly sowing seeds onto the surfaces of flooded paddy fields. At the yellow ripening stage or maturing stage, samples from 1.0 – 3.2 m² were harvested to measure the whole-crop and unhulled rice dry matter. In the trials at Joetsu and Tsukubamirai in 2011, dry matter was estimated from air-dried weight (Dry matter = Air-dried weight × 0.85), and unhulled rice weight was estimated from brown rice weight (Unhulled rice weight = Brown rice weight × 1.2). One-way analysis of variance (ANOVA) and Tukey-Kramer’s honestly significantly different (HSD) test were employed for statistical analysis. Location and cultivar were treated as factors and year as replication.
3. Evaluation of lodging resistance

Pushing resistance was evaluated by the method of Terashima et al. (1992) at NARO/WARC from 2009 – 2011. Plants were transplanted on 22 or 23 June of each year. The planting density was 16.7 hills m$^{-2}$ and three seedlings per hill were transplanted. Basal dressing was 5.6 g m$^{-2}$ nitrate as a slow-release fertilizer. The pushing resistance of 8 – 10 hills of each cultivar was measured at 15 cm above the soil surface (0 – 45º) using a digital force gauge (RX-5, Aikoh Engineering, Osaka, Japan). Lodging index was calculated as follows: Lodging index = Vertical center of gravity × Fresh weight / Pushing resistance per hill / 100. Statistical analysis was carried out each year using one-way ANOVA and Tukey’s HSD test.

### Results and Discussion

In 2012, ‘Chugoku-shi 205’ was officially registered by MAFF under the name ‘Tachiayaka’. Multi-location trials were carried out from 2009 – 2011 to evaluate its adaptability to cultivation in the area from Hokuriku to Chugoku in Japan. The heading date, yellow ripening stage, and maturing stage of ‘Tachiayaka’ were comparable to those of ‘Hoshiaoba’ and significantly earlier than those of ‘Tachisuzuka’, while culm length and panicle number were comparable to those of ‘Hoshiaoba’ (Table 3). Because several rachis branches close to the neck node had degenerated, the panicles of ‘Tachiayaka’ and ‘Tachisuzuka’ both appeared to be very short (Fig. 3).

Whole-crop yield is the most important trait of a WCS cultivar. Whole-crop dry-matter yield of ‘Tachiayaka’ ranged from 14.5 – 19.8 10$^2$ g m$^{-2}$, 92 – 104% of that of ‘Hoshiaoba’ (Table 3). No significant difference was observed in any trials. The extraordinarily low grain/straw ratio of ‘Tachisuzuka’ improved in value for WCS (Kouno, 2011). Yields of unhulled rice of ‘Tachiayaka’ were clearly lower than those of ‘Hoshiaoba’ and comparable to that of ‘Tachisuzuka’. Additionally, the growth and yield traits of ‘Tachiayaka’ cultivated via direct seeding and transplanting were comparable. Furthermore, there were no visible problems with seedling establishment and lodging. These results suggest that ‘Tachiayaka’ is suitable for direct seeding.

In breeding of rice cultivars for WCS, lodging resistance is one of the most important characters (Nakagomi et al., 2006; Sakai et al., 2008; Ohta et al., 2010). Therefore, to determine the lodging resistance of ‘Tachiayaka’, we investigated the pushing resistance and other characters associated with lodging (Table 4). The pushing resistance
per hill of ‘Tachiayaka’ was higher than that of ‘Hoshiaoba’, and the vertical centers of gravity of ‘Tachiayaka’ and ‘Tachisuzuka’ were lower than that of ‘Hoshiaoba’, likely a result of fewer grains per panicle. Therefore, the lodging index of ‘Tachiayaka’ was lower than that of ‘Hoshiaoba’ and comparable to that of ‘Tachisuzuka’. The high lodging resistance of ‘Tachiayaka’ enables its cultivation in regions where lodging caused by wind, rainfall, or other factors occurs frequently.

The rice cultivar ‘Tachisuzuka’, which was developed by breeders including us, is valuable for use as WCS, but a short-panicle cultivar that matures earlier is required for cultivation in northern and high-altitude areas. The findings presented here suggested that ‘Tachiayaka’ can be cultivated in a wide area of Japan. This study demonstrated the yield and lodging resistance of ‘Tachiayaka’, a newly developed short-panicle rice cultivar for use as WCS. ‘Tachiayaka’ has agronomical characteristics similar to those of ‘Tachisuzuka’ but matures earlier and should extend the harvest season for farmers cultivating short-panicle rice for WCS. Furthermore, ‘Tachiayaka’ can be grown for use as WCS in a wider area than ‘Tachisuzuka’. Because of its rapid maturation time, ‘Tachiayaka’ should be cultivable in the Hokuriku region of Japan. We also expect to obtain positive results in future adaptability trials in the southern Tohoku region and in high-altitude areas of southern Japan.

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