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REVIEW

Development of Rice Varieties for Whole Crop Silage (WCS) in Japan

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Abstract

Over-production of rice has been a problem for the past 40 years in Japan. On the other hand, there is also a need for an increase in the production of domestic bulk feed in Japan. Whole crop silage (WCS) rice is being promoted by the government. The whole aerial parts consisting of grains, leaves and stems are harvested at the yellow ripening stage. At present, about 12 WCS rice varieties have been bred and are commonly used in Japan. The total digestible nutrients (TDN) yields of WCS varieties are 3 to 27% higher than those of ordinary rice varieties. The lodging resistances of most of the WCS varieties are "High". Most WCS varieties are basically Japonica, but a few Indica varieties have been used in their parentage.

Discipline: Plant breeding
Additional key words: brown rice yield, dairy and beef cattle, lodging resistance, stem and leaf yield, total digestible nutrients (TDN) yield

Introduction

Japanese calorie based self-sufficiency in food was only 39% in 2006, despite the fact that many governmental efforts have been made toward lifting it. Per capita rice consumption is decreasing while per capita dairy and meat consumption is increasing in Japan. Over-production of rice has been a problem for the past 40 years. There are 2.6 million ha of paddy fields in Japan, of which about 1 million ha have been transferred to the production of other crops. Soybean, maize, wheat, and other upland crops are being currently recommended as substitutes for rice. In reality, ill-drained paddy fields throughout Japan are not really suitable for such upland crops. Consequently, most of the paddy fields are left fallow. On the other hand, the production of domestic bulky feed such as timothy grass and Italian ryegrass for dairy and beef cattle has not been able to catch up with the constant increase in per capita dairy and meat consumption in Japan. Some of the bulky feed is imported from America, Canada and China at a high cost due to their bulk and the distance involved in their transportation. Also, in view of the danger of the spread of foot-and-mouth disease from other countries, there is a strong demand for safe, locally produced dairy and meat products using domestic feed. Thus, there is a need for an increase in the production of domestic bulk feed in Japan. In addition, the disposal of animal waste has always been a serious problem which needs to be tackled.

The original habitat of rice is swampy areas and rice is the most suitable crop in ill-drained fields. If we can use the fallow rice fields for animal feed rice production, all of the above-mentioned problems will be solved simultaneously. In addition, it is easy to introduce animal feed rice to farmers because most of the techniques are similar to those applied in ordinary rice production. Furthermore, collaboration is feasible between rice growers and livestock farmers in the usage of animal waste as fertilizer. There are several types of animal feed rice. Rice straw for animal feed is being used, but the nutritional value is low. Brown rice and soft grains are good as concentrate, but their price is much higher than imported ones. Whole crop silage (WCS) rice is roughage and the preference of cattle for WCS is high. Domestic bulky feed production has great economic potential. This is because the cost of importing bulky feed is high due to its bulkiness. Domestic bulky feed can be competitive against

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imported ones. For the above-mentioned reasons, WCS rice is being promoted by the Ministry of Agriculture, Forestry and Fisheries.

The subsidies for WCS rice production and its usage for animal feed have been introduced in Japan since 2000. The cutting roll balers for WCS rice in the paddy fields were also developed[24]. These roll balers are a self-propelling type with rubber crawlers. One of them has the pre-treatment equipment of a head-feeding rice combine harvester and a bale chamber. When the crop is being harvested, lactic acid bacterium is sprayed to improve the quality of the silage[1]. Then, they are rolled into bales by roll-balers and wrapped in stretch film by bale wrappers.

Other East Asian countries including Korea, China and Taiwan, are facing similar problems relating to the increase in the consumption of dairy and meat products and over-production of rice[22]. Some researchers and policy makers in these countries are also considering the feasibility of using rice for dairy and beef cattle feed.

Objectives and cross combinations for WCS rice breeding

The necessary traits of WCS rice varieties are different from those of ordinary rice varieties. In the case of WCS rice varieties, the whole aerial parts consisting of grains, leaves and stems are harvested at the yellow ripening stage. As the degree of ripeness progresses, digestibility decreases and the productivity of WCS increases. The total digestible nutrients (TDN) are highest at the yellow-ripe stage, which is about 30 days after flowering and 10 to 15 days before the full ripening stage. When deciding which WCS rice variety is most suitable for a certain area, high TDN yield is the most important factor.

To accomplish the high TDN yield goal, heavy application of fertilizer to increase the plant size is necessary. However, heavy application of fertilizer usually results in a higher occurrence of lodging. Therefore, it is also crucial to improve the lodging resistance of WCS rice varieties (Photo 1). With improved lodging resistance, it will enable us to apply a large amount of fertilizer in paddy fields to increase the yield, and at the same time resolve the problem of having to dispose of a large amount of waste from animal husbandry. This high level of lodging resistance is also beneficial to the application of direct seeding cultivation which would reduce the cost of production. The selection of lines with other traits such as high germination rate from the soil and high-yielding in direct seeding conditions is also necessary.

As a WCS variety, "slightly easy" viviparity and resistance to shattering are also favorable because both

Photo 1. A standing WCS breeding line (left) and ordinary rice variety "Nipponbare" (right) in a field with nitrogen applied at 32 kg/10 a

Photo 2. Leaf Star has smaller panicles but long and thick stems

traits can reduce the probability of voluntary seedlings in ordinary rice production fields in the following year. In addition to that, easy shattering causes yield loss. From the point of view of low-cost and safe production, disease and pest resistance is also required. Blast is the most devastating rice disease in Japan.

At present, about 12 WCS rice varieties[2–6,8,10,11,14,17–19,21,23,26] have been bred and are commonly used in Japan. Most of the varieties were bred under the project "Integrated research for developing Japanese-style forage feeding system to increase forage self-support ratio", which is supported by the Ministry of Agriculture, Forestry and Fisheries of Japan. The cross combinations and origins of these varieties are shown in Table 1. Underlined parts of the names of the varieties indicate that they are Indica varieties. Partially underlined names indicate those that originated from Indica and Japonica crosses, and the length of the underline is roughly proportional to the ratio of Indica ancestors. With the exception of Minami-yutaka and Moretsu, most WCS varieties are basically Japonica, but a few Indica varieties have been used in their parentage. Nevertheless, it is considered that the higher

Table 1. The cross combinations of WCS rice varieties

Variety	Cross combinations
Yumeaoba	Jyo321 (Akihikari//Suweon258 (Suweon232/IR24) /Akihikari) / Fukuhibiki (Kochihibiki/Ouu316)
Bekoaoba	Oochikara (BG1/Shu3116) / Saikai203 (Ouu326//Suweon258/Tainung67)
Kusayutaka	Chugoku105 (Chugoku80/KantoPL3) /Oochikara
Hoshiaoba	Chugoku113 (Suweon258/Ooseto//Chugoku69) /Oochikara
Minamiyutaka	γray induced mutant line from Moretsu
Moretsu	MNU induced mutant line from Linx89
Nishiaoba	Oochikara / Saikai187 (Kochihibiki//BG25/Kanto124)
Kusahonami	Akenohoshi (Chugoku55/KC89) / Chugoku113 (Suweon258/Ooseto//Chugoku69)
Kusanohoshi	Tashukei175 (Suweon258/Ooseto//Cyugoku69) / Akenohoshi
Hamasari	Tamakei62 (Chugoku49/Etsunan77) /F5-1816 (IR279/Nipponbare)
Leaf Star	Chugoku117 (B581/NaeguriB40) /Koshihikari
Tachiaoba	Hakei906/ (47-1-1 (Lemont/Saikai205) /95SH50 (Ouu342/Aichi92))

Underlined parts of the names of the varieties indicate the ratio of Indica ancestors.
Data are cited from the records of varietal registration.

WCS yield and the major resistance genes for rice blast and stripe originated from those Indica parents.

Agronomical traits of newly bred WCS rice varieties

The agronomical traits of 12 WCS varieties are shown in Table 2. The varieties are arranged in the order of their heading dates when grown in Ibaraki Prefecture which is located 40 km northeast of Tokyo. Accurate comparisons can only be made among control varieties tested in the same institutes. The whole crop yields of WCS varieties were about 1 to 24% higher than those of ordinary varieties. Brown rice yields ranged from 22% lower to 29% higher compared with ordinary varieties. The percentages of the TDN of whole crop yields for both WCS and ordinary rice varieties were all around 60%. The TDN yields of ordinary rice varieties for human consumption are 0.77 to 1.01 t/10 a. In fact, recently bred WCS rice varieties showed an increase in TDN yields to about 1.19 t/10 a. The TDN yields of WCS varieties are 3 to 27% higher than those of ordinary varieties because of their higher whole crop yields. Our primary objective in the development of WCS rice is to increase the TDN yield to 1.3 t/10 a, a level comparable to that of forage corn.

Table 3 shows the traits of WCS rice varieties. Koshihikari is an ordinary rice variety for human consumption, and its planted area accounts for about 40% of the total paddy area in Japan. Its lodging resistance was "Very low". The lodging resistances of most of the WCS varieties were "High". The exception was Nishiaoba, having only moderate lodging resistance. Nishiaoba was selected as a recommended variety for Oita Prefecture, where the yield there was high and the overall performance was good. The high lodging resistance of the other varieties can be attributed to thick culms, physical strength of stems (Leaf Star[15]) and thickness of roots (Tachiaoba[18]).

Most of the WCS varieties have major gene resistance for rice blast. However, major gene resistance for blast can be broken down easily. After such a breakdown, partial resistance is of critical importance. Unfortunately, their partial resistance is still largely unknown. In the case of direct seeding rice between rows of wheat or barley, rice stripe virus is also common. Many WCS rice varieties are resistant to this. Another problem is that although cold tolerance during the anther development period is important in the northern and highly elevated areas in Japan, Yumeaoba and Bekoaoba which were bred for the northern areas of Japan do not have sufficient cold tolerance. As to resistance to shattering, with the exception of Moretsu, all of the WCS varieties are resistant. Moretsu was bred by a private company, Kirin Brewery Co., Ltd. However, Minamiyutaka, a gamma ray-irradiated mutant variety of Moretsu bred by the Miyazaki Agricultural Experiment Station, has overcome this deficiency in shattering-resistance.

The 1,000–grain weights of Yumeaoba, Bekoaoba, Kusayutaka, and Hoshiaoba were 26 to 35 g. They were much higher than those of ordinary varieties. These varieties achieved higher yields due to a higher brown rice yield. The culm lengths of Nishiaoba, Kusahonami, Kusanohoshi, and Tachiaoba were relatively long, and they can achieve high whole crop yields in terms of both high brown rice yields and stem and leaf yields. On the other hand, the brown rice yields of Minamiyutaka, Moretsu,

Table 2. Agronomical traits of newly bred WCS rice varieties at each breeding institute

Variety (Control Variety)	Location of breeding institutes	Heading Date	Culm length (cm)	Air-dried whole crop yield (t/10 a)	Whole crop yield (t/10 a)	Brown rice yield (t/10 a)	TDN content (% of dry matter)	TDN yield (t/10 a)	Relative value of TDN (%)
Yumeaoba	Niigata	July 29	86	1.73	1.52	0.72	61.2	0.93	105
(Fukuhibiki)		July 27	78	1.61	1.44	0.74	61.6	0.89	100
Bekoaoba	Akita	Aug. 7	70	1.77	1.37	0.73	61.9	0.85	110
(Fukuhibiki)		Aug. 4	72	1.54	1.23	0.69	62.9	0.77	100
Kusayutaka	Niigata	Aug. 5	87	1.71	–	0.73	58.1	0.94	103
(Oochikara)		Aug. 6	88	1.70	–	0.70	58.9	0.91	100
(Kinuhikari)		Aug. 6	85	1.64	–	0.63	–	–	–
Hoshiaoba	Hiroshima	Aug. 13	101	1.91	1.52	0.71	58.6	0.91	103
(Kusahonami)		Aug. 24	96	1.86	1.50	0.61	58.3	0.88	100
Minamiyutaka	Miyazaki	Aug. 28	101	1.47	–	0.31	–	–	–
Moretsu		Aug. 28	104	1.37	–	0.27	–	–	–
(Yumehikari)		Aug. 30	71	1.38	–	0.40	–	–	–
Nishiaoba	Fukuoka	Aug. 19	105	2.24	1.97	0.65*	59.3	1.17	115
(Nishihomare)		Aug. 21	93	1.94	1.72	0.56*	59.1	1.01	100
Kusahonami	Ibaraki	Aug. 24	95	2.08	1.85	0.67	59.2	1.10	105
Hamasari		Aug. 30	86	1.90	1.67	0.46	61.1	1.05	100
(Nipponbare)		Aug. 15	88	1.80	–	0.52	–	–	–
Kusanohoshi	Hiroshima	Aug. 28	104	2.06	1.63	0.65	57.1	0.94	107
(Kusahonami)		Aug. 24	96	1.86	1.50	0.61	58.3	0.88	100
Leaf Star	Ibaraki	Aug. 31	109	2.14	1.92	0.42	61.0	1.17	111
(Hamasari)		Aug. 31	96	1.92	1.73	0.51	60.7	1.05	100
Tachiaoba	Fukuoka	Aug. 29	106	2.41	2.13	0.66	55.7	1.19	127
(Minamihikari)		Aug. 25	86	1.95	1.69	0.56	55.4	0.93	100

Data are cited from the records of varietal registration and additional data form each breeding institute.
*: Grain yield. –: Unknown or not available. The varieties bred by 2006 were included.

Nishiaoba, Hamasari, and Leaf Star were much lower than those of the others (Photo 2). Despite that, the high TDN yield of Leaf Star is attributed to its high leaf and stem yields. The high TDN yield of Kusahonami was due to high brown rice yields and leaf and stem yields. According to the data for Holstein steer feed, the percentages of the TDN between Kusahonami and Leaf Star showed very little difference (Table 4). It is considered that the whole crop yield increase for either grain or leaf and stem was equal to the increase in the percentage of TDN. This is because the nonstructural carbohydrate content in the stem and leaf sheath of Leaf Star is high[9], although the TDN percentage of grain is generally higher than those of stem and leaf. This means that it is feasible to use a higher foliage but low grain yield plant type. Meanwhile, the smaller amount of non-digested excreted grain of Leaf Star has practical advantages. For dairy cattle farmers, a lot of undigested grain excretion in cattle waste is not preferable even if the TDN percentages are the same.

Figure 1 shows the suitable areas for cultivating WCS rice varieties. Except for Hokkaido and the northern areas of Tohoku, WCS rice varieties cover all parts of Japan. High TDN and cold tolerant WCS varieties are urgently needed in Hokkaido and the northern areas of Tohoku. Compared to ordinary rice varieties, WCS rice is harvested at the yellow-ripe stage, which is 10 to 15 days earlier than the ripening stage. This earlier harvesting makes it possible for us to use varieties with later heading dates, as late as the end of August in the Kanto area.

In general, the palatability of rice WCS for cattle is the same or even better than that of timothy grass and Italian ryegrass. In addition, because of its high Vitamin E contents, the meat of WCS-fed cattle can stay fresh longer than that of cattle fed with rice stover, timothy grass and Italian ryegrass[12].

Potentials of the development of WCS rice varieties

Developing extremely high dry matter varieties for

Table 3. Traits of WCS rice varieties

Variety	Lodging resistance	Viviparity	Shattering	Leaf blast		Rice stripe resistance	Cold tolerance of anther	1,000–grain brown rice weight (g)
				Major gene	Partial resistance			
WCS rice varieties								
Yumeaoba	Very high	Moderate	Resistant	*Pita-2,Pib*	–	Resistant	Slightly low	26.5
Bekoaoba	High	Slightly easy	Resistant	*Pita-2 or Pita*	Slightly low	Susceptible	Low	30.6
Kusayutaka	High	Slightly easy	Resistant	*Pia,Pik*	Moderate	Susceptible	Low	35.0
Hoshiaoba	Slightly high	Slightly easy	Slightly resistant	*Pita-2,Pib*	–	Resistant	–	29.4
Minamiyutaka	High	Easy	Resistant	–	–	Resistant	–	17.2
Moretsu	High	Slightly easy	Very easy	–	–	Resistant	–	16.9
Nishiaoba	Moderate	Easy	Resistant	*Pia,Pikm*	Moderate	Susceptible	–	29.3
Kusahonami	High	Slightly easy	Resistant	*Pia,Pii,Pik+α*	–	Resistant	–	21.7
Kusanohoshi	Slightly high	Resistant	Resistant	*Pita-2,Pib*	–	Resistant	–	24.3
Hamasari	High	Resistant	Resistant	*Pia,Pish*	Slightly high	Resistant	–	–
Leaf Star	High	Slightly easy	Resistant	*Pia,Pik*	Very high	Susceptible	–	20.3
Tachiaoba	Very high	Moderate	Resistant	*Pia,Pii*	Moderate	Resistant	–	22.2
Ordinary rice varieties								
Nipponbare	Slightly high	Resistant	Resistant	*Pia*	Moderate	Susceptible	Very low	20.4
Nishihomare	Slightly high	Slightly easy	Slightly easy	*Pia*	Moderate	Susceptible	–	21.2
Koshihikari	Very low	Highly resistant	Resistant	+	Low	Susceptible	High	20.6

Data are cited from the records of varietal registration. –: Unknown or not available. +: No effective major genes for blast.

Table 4. Percentages of TDN and grain excretion of WCS dry matter for Holstein steers feed

Item	Whole crop rice silages		Se*
	Kusahonami	Leaf Star	
TDN (%)	45.4	45.8	1.9
Grain excretion (%)	5.2	2.4	1.1

*: Standard error of means.

increasing the TDN yield is the objective of this project. There are two possible ways to achieve higher TDN yields. We can increase either the grain yield or the stem and leaf yield. The grain types will be used mainly for beef cattle and the stem and leaf types will be used for both beef and dairy cattle because of their lower level of undigested grain excretion in waste.

Culm length is generally long in the stem and leaf types. Its leaf area density seems to be low. This trait is considered to be an advantage in achieving higher yield because of the improvement of gas diffusion inside rice stands[7,20]. Dry matter yield of over 3 t/10 a was obtained from Rayada which is a deepwater and extremely late maturing rice variety[16]. Its plant height is very high although there is no panicle formation in mainland Japan. Its yield performance was relatively high even in lower

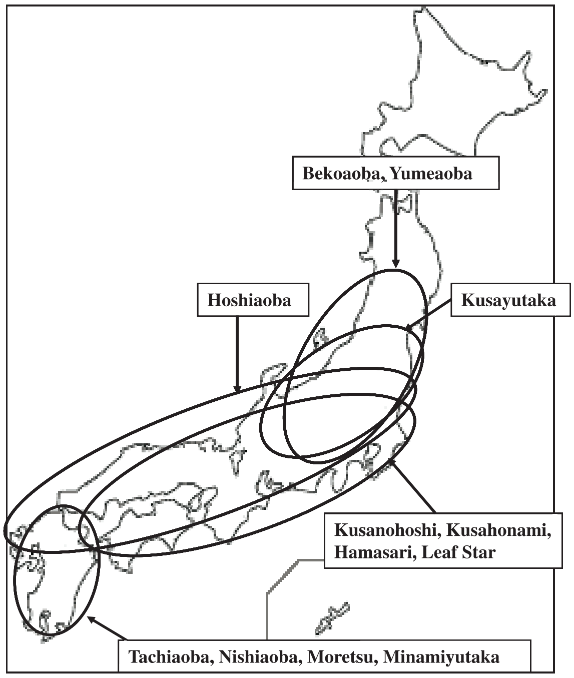

Fig. 1. Areas suitable for WCS rice varieties

fertilizer conditions[25]. The plant height of Taporuri was 200 cm and dry matter yield was 2.4 t/10 a in twice harvesting[13]. In addition to the above mentioned varieties, new genetic resources are going to be used for the further improvements of WCS rice varieties.

High nonstructural carbohydrate content in the stem and leaf sheath of Leaf Star may contribute to maintaining its TDN content. One of the breeding objectives is to increase the nonstructural carbohydrate content. The development of varieties with lower lignin content is being conducted for the improvements of the TDN content and digestibility[15]. Lower silica content or fewer brittle culm rice traits may also be useful for attaining higher digestibility. Rice varieties with much higher stem and leaf yield can be developed by using male sterilities or small panicle traits. Since the development of WCS rice is a relatively new approach, more daring trials should be attempted. However, digestibility tests have to be conducted to confirm their effectiveness.

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