JARQ 58 (4), 177-183 (2024) https://www.jircas.go.jp

REVIEW

Characteristics of Rice Varieties for Commercial Use and Livestock Feed and Their Cultivation Technology in the Cold Region of Japan

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Abstract

A decrease in the number of farmers, enlargement of the management scale, and diversification of rice usage are predicted for rice cultivation in Japan. Conventionally, branded rice varieties with weak lodging resistance are cultivated under low-nitrogen conditions to produce low-yield, high-priced rice with a taste suitable for household consumption. In contrast, it is more effective to cultivate varieties with strong lodging resistance under high-nitrogen conditions to produce high-yield rice for commercial use and livestock feed. Cold regions (Tohoku region) are suitable for producing high-yield rice, although cold weather reduces variation in cultivation systems. For large-scale farms in cold regions, direct seeding, sparse transplanting, and late transplanting are promising strategies. We discuss the future directions of rice breeding and cultivation technologies for commercial use and livestock feed in cold regions.

Discipline: Crop Science
Additional key words: direct seeding, high-nitrogen application, high yield, late transplanting, sparse transplanting

Introduction

In Japan, the rice cultivation area is decreasing because of the decrease in rice consumption and large-scale rice production is becoming popular as the number of rice farmers is decreasing. Conversely, rice consumption is diversifying from home-cooked meals to commercial use. Against this background, to maintain rice cultivation that can generate stable profits, it is necessary to not only rely on popular branded rice for home use, as in the past, but also to develop rice cultivation for various purposes. Cold regions (Tohoku region) account for 28% of Japan's rice production in 2023 and have the highest yield in Japan. In this review, we discuss the characteristics and cultivation technology of rice varieties for commercial use, such as ready-made meals and in restaurants, and livestock feed, such as rice grain for feed (feed rice) and whole crop rice silage (rice WCS) in cold regions. The primary information in this review is based mainly on field experiments conducted by our research group at the Tohoku Agricultural Research Center, NARO, located in the Akita Prefecture (Fukushima 2020).

Historical changes in rice yield in cold regions

The rice yield in the cold regions was estimated to be 190-340 kg/10 a from 1900 to 1950. According to crop statistics published by the MAFF, it increased to 524 kg/10 a in 1980 and reached 568 kg/10 a by 2022. The factors contributing to the increase in yield include increases in nitrogen fertilization and new varieties. However, this is likely due to the advances in comprehensive cultivation technologies (Fukushima et al. 2018).

In cold regions, yields of 728-1028 kg/10 a were

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Received 27 October 2023; accepted 19 December 2023.

already recorded as the highest in a contest held in Japan pertaining to rice yield between 1949 and 1968. The rice yield in recent field experiments aimed at high yields in cold regions ranged from 963 to 983 kg/10 a (Mae et al. 2006, Fukushima et al. 2011). Compared with these potential yields, the yield of 559 kg/10 a from crop statistics was very low. One of the reasons for this is that popular branded varieties with low lodging resistance, such as "Akitakomachi" and "Hitomebore" are cultivated under low-nitrogen conditions. However, as described below, it is possible to increase yield by 20%-30% by cultivating varieties with high lodging resistance under high-nitrogen conditions.

Effects of climatic factors on rice yield in cold regions

Rice yield is the highest in the cold region of Japan. Murata (1964) suggested that the high yield in cold regions could be attributed to moderately low temperatures and high solar radiation during the grain-filling period. A comparison of recent field experiments in cold and warm regions revealed that although the top dry weight and leaf area at the full heading stage were larger in warm regions, the percentage of ripened grains was lower in warmer regions (Table 1; Fukushima 2021a). Consequently, the yield was lower in the warm regions. According to a recent analysis using the crop statistics of 41 prefectures in Japan, prefectures where the temperature before heading was low, including prefectures in cold regions, had high yields, although there was no clear relationship between the temperature after heading and yield (Figure 1; Fukushima 2021b). These results suggest that high temperatures before heading in warm regions resulted in overgrowth and a decrease in yield, whereas low temperatures before heading in cold regions resulted in high yields. In addition, low temperatures before and after heading in cold regions are related to the high grain quality. Conversely, low temperatures in cold regions make it difficult to extend the cropping period and increase the risk of cold damage, especially sterility, owing to low temperatures during the booting stage and the occurrence of rice blast.

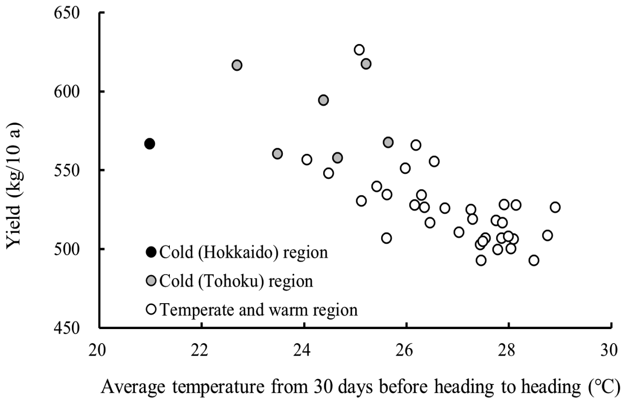
Characteristics of rice varieties for commercial use and feed

In rice cultivation for commercial use and feed, it is crucial to increase the yield per unit area to increase the income. However, the required grain quality and taste vary significantly depending on the intended purpose.

Table 1. Effects of meteorological factors on rice yield differences between cold and warm regions of Japan

Region	Variety	Transplanting date	Heading date	30 days before heading: Average temperature (°C)	30 days before heading: Average sunshine radiation (MJ m^{-2}day^{-1})	30 days after heading: Average temperature (°C)	30 days after heading: Average sunshine radiation (MJ m^{-2}day^{-1})	Top dry weight at the full heading stage (g m^{-2})	Leaf area at the full heading stage (m^{2}m^{-2})	No. of spikelets per area (m^{-2})	Percentage of ripened grain (%)	Yield (g m^{-2})
Cold	Akitakomachi	15-May	5-Aug	23.5	13.9	22.8	15.6	866	4.06	31910	91.9	665
Warm	Hinohikari	19-Jun	26-Aug	27.7	17.8	26.2	17.4	963	4.55	31903	84.8	620

Data were adopted from Fukushima (2021a).



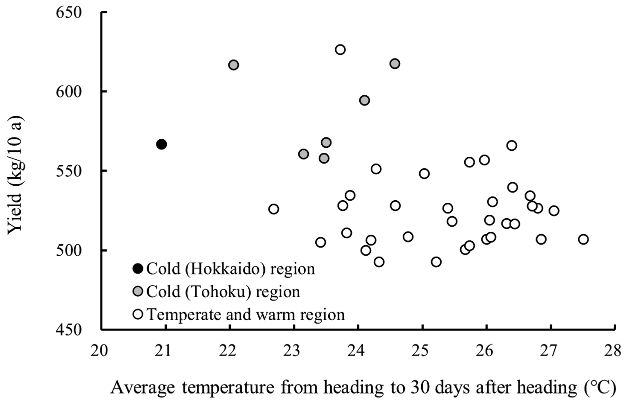


Fig. 1. Effects of temperature on regional differences in rice yield in Japan
Data were adopted from Fukushima (2021b).

According to interviews with farmers and wholesalers, it is desirable to maintain a certain level of good and stable grain quality for commercial use. Regarding taste, sticky rice is required for bento lunches and rice balls but is not suitable for sushi, rice bowls, and frozen fried rice. For feed rice, it is desirable that the grain quality be inferior from the standpoint of distinguishability from food rice. In addition, it is not necessary to consider taste, and it is desirable from a nutritional perspective that the grain protein content is high. Feed rice is expected to produce extremely high yields using high-yielding varieties with distinguishable inferior qualities, such as extra-large grain varieties, under high-nitrogen conditions. For rice WCS, total dry weight and silage quality should be excellent. The quality of silage varies depending on the type of cow used. Therefore, it is necessary to produce rice WCS according to these requirements (Fukushima et al. 2017a).

Rice cultivation technology for commercial use and feed

1. High-fertilization transplanting

The most effective way to increase yield is to cultivate varieties with high lodging resistance under high-nitrogen conditions. Rice varieties for commercial use and feed bred by the Tohoku Agricultural Research Center, National Agriculture and Food Research Organization (NARO), did not necessarily produce higher yields under low-nitrogen conditions (Fukushima et al. 2018c) compared to popular branded varieties in cold regions, but clearly produced higher yields under high-nitrogen conditions, mainly because of the severe lodging of the popular branded varieties. For example, the yields under the standard nitrogen condition of 7 kg N/10 a were 650 kg/10 a for the popular branded variety "Akitakomachi" and 705 kg/10 a in the commercially used variety "Chihominori" (Table 2). Conversely, the yields under the high-nitrogen condition of 12 kg N/10 a were 690 kg/10 a in "Akitakomachi" and 787 kg/10 a in "Chihominori" (Fukushima et al. 2017e). The yields under the standard nitrogen condition were 670 kg/10 a in the popular branded variety "Hitomebore" and 697 kg/10 a in the feed rice variety "Bekoaoba." The yields under high-nitrogen conditions were 694 kg/10 a in "Hitomebore" and 871 kg/10 a in "Bekoaoba" (Fukushima et al. 2018a).

The grain quality of commercially used varieties is the same as or slightly inferior to that of popular branded varieties. The taste of commercially used varieties is the same as that of popular branded varieties according to taste sensory tests. Although the taste of these varieties decreases under high-nitrogen conditions owing to the increase in grain protein, it has been suggested that the taste is marginally better in commercially used varieties under high-nitrogen conditions than in high-yielding varieties with a poor taste under standard nitrogen conditions (Fukushima et al. 2017e). As commercially used varieties are rarely required to have an excellent taste, it is possible to cultivate them under high-nitrogen

Table 2. Effects of high-nitrogen fertilization and direct seeding on the yield and quality characteristics of rice in cold regions of Japan

Cultivation method	Variety	Heading date	Culm length (cm)	No. of panicles (m^{-2})	1,000-grain weight (g)	Yield ($g\ m^{-2}$)	Lodging degree (0-5)	Grain quality (1-9)	Grain protein (%)
Transplanting under the standard-nitrogen conditions	Akitakomachi	31-Jul	86	474	22.4	650	2.4	4.3	6.81
	Chihominori	28-Jul	73	506	22.9	705	0.1	4.5	6.71
	Hitomebore	3-Aug	90	499	23.1	670	2.4	4.0	6.16
	Bekoaoba	3-Aug	69	349	32.1	697	0.0	8.5	6.03
Transplanting under the high-nitrogen conditions	Akitakomachi	31-Jul	93	518	22.0	690	3.2	4.6	7.80
	Chihominori	28-Jul	79	580	22.3	787	1.2	4.8	7.91
	Hitomebore	3-Aug	95	571	22.1	694	3.8	4.8	7.28
	Bekoaoba	3-Aug	74	393	31.7	871	0.1	8.4	6.96
Direct seeding under the high-nitrogen conditions	Akitakomachi	7-Aug	88	569	22.2	614	4.3	3.8	7.18
	Chihominori	6-Aug	74	617	22.5	746	2.1	4.0	6.80
	Hitomebore	14-Aug	90	616	22.1	592	3.9	4.4	7.04
	Bekoaoba	12-Aug	74	485	31.8	815	1.2	8.1	6.77

Akitakomachi, Hitomebore: popular varieties; Chihominori: commercially used variety; Bekoaoba: feed variety
Lodging degree: 0 (no lodging) to 5 (extensive lodging); grain quality: 1 (very superior) to 9 (very inferior)
Data were adopted from Fukushima et al. (2017d) and Fukushima et al. (2018a).

conditions. However, under extremely high-nitrogen conditions, commercially used varieties do not yield higher yields and sometimes lodge. Although feed varieties have strong lodging resistance, they do not necessarily show higher yields with excessive nitrogen fertilization. Therefore, it seems desirable to apply 1.5 times the normal amount of nitrogen for commercially used varieties and 1.8 times the normal amount of nitrogen for feed varieties. It is not necessary to accurately set the timing and amount of topdressing for commercial use and feed, although early topdressing may result in a low percentage of ripened grains and inferior grain quality due to an excessive number of spikelets, and late topdressing may lead to an increase in grain protein and a decrease in taste (Fukushima et al. 2017b).

2. Direct seeding

Direct seeding is not necessarily low-cost because of the high cost of herbicides; however, it is expected to be a technology for skipping seedling raising in large-scale rice farming. In cold regions, direct seeding tends to produce lower yields than transplanting (Yoshinaga et al. 2008). However, it is possible to increase the yield of direct seeding using lodging-resistant varieties under high-nitrogen conditions, in which popular branded varieties are heavily lodged. For example, the yield of a popular branded variety "Akitakomachi" with transplanting under standard nitrogen conditions was 650 kg/10 a, whereas that of a commercially used variety "Chihominori" with direct seeding under high-nitrogen conditions was 746 kg/10 a (Table 2; Fukushima et al. 2017f). The yield of the popular branded variety "Hitomebore" with transplanting under standard nitrogen conditions was 670 kg/10 a, whereas that of a feed rice variety "Bekoaoba" in direct seeding under high-nitrogen conditions was 815 kg/10 a (Fukushima et al. 2018a). The grain quality of direct seeding was the same as or marginally better than that of transplanting. This is considered to be due to the low ripening temperature and small number of spikelets per panicle in direct seeding (Yoshinaga et al. 2012). The taste of direct seeding did not differ from that of transplanting. For direct seeding, varieties with excellent seedling establishment are required (Fukushima et al. 2017d). Other varietal characteristics suitable for direct seeding did not differ from those suitable for transplanting. However, because direct seeding requires a long growth period, early maturing varieties are desirable for direct seeding in cold regions.

3. Sparse transplanting

Sparse transplanting has attracted attention as a method to reduce the number of seedling boxes. In cold regions, the number of panicles per unit area was smaller, but the number of spikelets per panicle was larger in sparse transplanting than in standard transplanting. The yield did not differ between the sparse and standard transplanting groups. Although it has been believed that sparse transplanting is not suitable for varieties with large but few panicles, no varietal differences were observed in the adaptability for sparse transplanting, including the feed rice variety "Iwaidawara" with large but few panicles

Table 3. Effects of transplanting density on yield and quality characteristics of rice grown in cold regions of Japan

Variety	Transplanting density	Heading date	Culm length (cm)	No. of panicles (m^{-2})	No. of spikelets per panicle	Percentage of ripened grains (%)	1,000-grain weight (g)	Yield ($g\ m^{-2}$)	Lodging degree (0-5)	Grain quality (1-9)	Grain protein (%)
Chihominori	Normal	28-Jul	69.0	499	64	92.9	22.1	613	0.1	4.3	7.09
	Sparse	28-Jul	70.7	398	77	93.0	22.1	593	0.2	4.6	7.08
Iwaidawara	Normal	29-Jul	78.3	296	113	83.9	26.3	698	0.0	7.2	6.43
	Sparse	30-Jul	79.3	265	125	88.4	25.8	693	0.0	7.2	6.49
Akitakomachi	Normal	30-Jul	81.0	479	62	89.8	21.9	601	1.3	4.2	7.09
	Sparse	31-Jul	81.7	368	75	92.4	22.2	596	0.5	4.2	7.05
Hitomebore	Normal	4-Aug	80.7	513	57	93.0	22.5	662	2.1	4.3	6.52
	Sparse	5-Aug	83.3	418	73	94.3	22.3	648	1.4	4.3	6.34
Eminoaki	Normal	5-Aug	62.0	496	61	93.5	22.5	569	0.0	3.8	6.72
	Sparse	7-Aug	65.7	413	71	90.8	22.2	571	0.0	3.8	6.71
Average of 5 varieties	Normal	1-Aug	74.2	457	71	90.6	23.1	629	0.7	4.8	6.77
	Sparse	2-Aug	76.1	372	84	91.8	22.9	620	0.4	4.8	6.73

Akitakomachi, Hitomebore: popular varieties; Chihominori, Eminoaki: commercially used varieties; Iwaidawara: feed variety
Lodging degree: 0 (no lodging) to 5 (extensive lodging); grain quality: 1 (very superior) to 9 (very inferior)
Data were obtained from Fukushima et al. (2018d).

(Table 3; Fukushima et al. 2018d). Consequently, sparse transplanting is considered effective for rice varieties for commercial use and feed, although there are some reports that the grain quality marginally decreases and grain protein marginally increases with the sparse transplanting of branded varieties.

4. Late transplanting

As the rice cultivation area of each farm has increased, it has become necessary to extend the transplanting and harvesting periods. In cold regions, it is difficult to raise seedlings and transplant them early because of the residual snow and low temperatures in early spring. Therefore, late planting is the primary method used to extend the transplanting period. Compared with conventional transplanting in mid-May, late transplanting in mid-June reduced the yield by approximately 15% because of a decrease in the number of panicles per unit area and percentage of ripened grains (Table 4; Fukushima et al. 2018b). Grain quality in late transplanting was marginally better than that in conventional transplanting. The taste of late transplanting did not differ from that of conventional transplanting. Late transplanting is effective for dispersing the harvest period. Therefore, late transplanting can be performed if it is beneficial in large-scale management. Because the main reason for the low yield in late transplanting is the lack of temperature and sunshine hours during the grain-filling period due to late heading, it is considered desirable to use early maturing varieties.

Prospects for rice breeding and rice cultivation technology for commercial use and feed

1. Prospects for breeding in the short and medium terms

Although the commercially used varieties with strong lodging resistance bred by the Tohoku Agricultural Research Center, NARO, were able to achieve high yield under high-nitrogen conditions, the yield was not as high as that of the high-yielding variety "Fukuhibiki," the quality and taste of which are insufficient for commercial use (Fukushima et al. 2017e). In temperate regions, the new variety "Niji-no-kirameki," which had a slightly heavy 1,000-grain weight and high ripening ability, achieved both a higher yield and grain quality in comparison with a popular branded variety "Koshihikari" (Fukushima 2022). Similarly, commercially used varieties with both high yields and grain quality are expected to be bred in cold regions. Regarding the taste, until now, the main breeding goal is to produce sticky varieties similar to "Koshihikari." However, for commercial use, several types of taste are required. Low-amylose varieties are desirable for chilled cooked rice because they do not become hard during low-temperature storage. Varieties with a slightly higher amylose content are desirable for rice bowls, sushi, and frozen fried rice.

Regarding varieties for feed rice, it is difficult to breed extremely high-yield varieties that clearly surpass "Fukuhibiki" and "Bekoaoba." The short-term goal may be to develop varieties with stable and high yields, including superior seedling establishment in direct seedlings, cold tolerance, and field resistance to blast diseases. Regarding rice WCS, varieties with small panicles and large stems and leaves, such as "Tachisuzuka," are popular in western Japan because of their high silage quality (Matsushita et al. 2012). It is desirable to develop early maturing varieties with small panicles, large stems and leaves that are suitable for cold regions (Fukushima et al. 2017a).

2. Prospects for long-term breeding

In the long term, useful genes are expected to be introduced and accumulated from a wide range of genetic resources to breed epoch-making varieties. The yield can be analyzed by dividing it into sink capacity and sink filling. It is easy to genetically expand sink capacity by

Table 4. Effects of transplanting time on the yield and quality characteristics of rice in cold regions of Japan

Transplanting time	Variety	Heading date	Culm length (cm)	No. of panicles (m^{-2})	No. of spikelets per panicle	Percentage of ripened grains (%)	1,000-grain weight (g)	Yield ($g\ m^{-2}$)	Lodging degree (0-5)	Grain quality (1-9)	Grain protein (%)
Normal	Chihominori	27-Jul	74	519	73	90.3	22.1	730	0.1	4.0	6.89
	Akitakomachi	29-Jul	88	497	71	91.1	22.0	675	2.8	4.0	7.30
Late	Chihominori	16-Aug	78	463	70	83.2	22.8	611	0.0	3.4	6.51
	Akitakomachi	16-Aug	91	412	74	84.2	22.3	576	1.6	3.6	6.98

Akitakomachi: popular variety; Chihominori: commercially used variety
Lodging degree: 0 (no lodging) to 5 (extensive lodging); grain quality: 1 (very superior) to 9 (very inferior)
Data were obtained from Fukushima et al. (2018b).

increasing husk size because it does not have a strong negative correlation with the number of spikelets per panicle or the number of spikelets per area (Fukushima et al. 2017d, 2018a, 2018c). In addition, some indica-type varieties have an extremely large number of spikelets per unit area due to the excellent development of tillers and panicle branchings (Fukushima 2019). However, it is not possible to increase the yield simply by expanding the sink capacity because there is a strong negative correlation between sink capacity and sink filling.

We attempted to evaluate and introduce the genes *APO1* and *TAWAWA1*, which increase the number of spikelets per panicle (Fukushima et al. 2017c) and erect panicle trait (Fukushima et al. 2014a) in cold regions. However, these genetic traits did not increase the yield because of their low sink-filling ability. It is difficult to identify the genetic factors that increase sink filling because many factors are involved in dry matter production and its distribution to the panicle. Furthermore, it is crucial to clarify the genetic factors that limit the yield under cold conditions. Ultimately, it is necessary to continue research on various aspects, from the genetic level to adaptability to cold conditions.

3. Prospects for cultivation technology

Many high-yield rice cultivation technologies, such as "a supplement fertilizer to the deep soil layer" (Tanaka 1983) and "ideal rice cultivation" (Matsushima 1973) have been proposed for a long time. However, when cultivating high-yielding varieties with strong lodging resistance under high-nitrogen conditions, it is difficult to increase yield using detailed growth control techniques, such as topdressing timing and transplanting density (Fukushima et al. 2011). For commercially used feed varieties that require labor reduction and low costs, there is little room for improving yields through detailed growth control techniques in each paddy field. Rather, the comprehensive management of many paddy fields on large-scale farms will become more crucial (Ishikawa et al. 2021).

Large-scale farmers are expected to increase the ratio of labor-saving direct seeding. In cold regions, it is common to sow directly in mid-May, immediately before the peak transplanting season. However, if the direct seeding period could be extended, there would be significant benefits for large-scale management. There are several types of direct seeding methods. Direct seeding in well-drained fields is useful for early sowing, while very early maturing varieties are crucial for late sowing. Seedling establishment at low temperatures must be improved for direct seeding in flooded fields.

Conclusion

This review discusses rice varieties and their cultivation technologies for high incomes in cold regions. The basic technology is to increase the yield per unit area by cultivating varieties with strong lodging resistance under high-nitrogen conditions. Furthermore, we demonstrated the possibility of cost and labor reduction and work distribution using direct sowing, sparse planting, and late planting. Although this review focuses on our research in one of the cold regions, we believe that many of the findings can also be applied to other regions of Japan.

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