Opinion

Breeding Temperate Japonica Rice Varieties Adaptable to Tropical Regions: Progress and Prospects

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Abstract: Temperate *japonica* rice is mainly cultivated in temperate regions. Many temperate *japonica* varieties have a superior grain quality that is preferred in Northeast Asian countries such as Japan, Korea, and China. The changes in consumers' preferences in Southeast Asia and Western countries has contributed to increasing the demand for temperate *japonica*. Most temperate *japonica* varieties developed in temperate regions typically exhibit extra-early flowering under the short-day conditions in the tropics, which usually results in severely reduced yields. Since 1992, we have been developing temperate *japonica* varieties that can adapt to tropical environments to meet the increasing demand for temperate *japonica* rice, having released six varieties in the Philippines. Especially, the yield of one of the temperate *japonica* varieties, Japonica 7, was comparable to the yields of leading *indica* varieties in the Philippines. Here, we discuss the current breeding initiatives and future plans for the development of tropical-region-bred temperate *japonica* rice.

Keywords: *Oryza sativa* L.; temperate *japonica*; tropical region; adaption; breeding

1. Introduction

Japonica rice, a subspecies of *Oryza sativa* L., can thrive in tropical and temperate zones; hence, it can be divided into two subgroups: temperate *japonica* and tropical *japonica* [1]. Tropical *japonica* is cultivated in Southeast Asian countries such as the Philippines and Indonesia, while temperate *japonica* is mostly grown in North-East Asian countries such as Japan, Korea, and China, where the seasonal changes in climate temperature are distinct. Globally, temperate *japonica* is more produced and consumed than tropical *japonica* [2]. Due to the unique attributes of temperate *japonica* varieties such as their sticky texture, they are often classified as special-purpose rice in the regions where *indica* rice is predominantly consumed or rice is not the primary staple food [3]. Many temperate *japonica* rice varieties are valued for their sticky texture and high grain quality that are distinct from those of *indica*. However, due to the poor adaptability of many temperate *japonica* rice plants to

tropical environments, the production of temperate *japonica* rice has been very limited in the Southeast Asian countries. Sustaining an adequate supply is becoming more challenging mainly due to factors such as the low yield potential of *japonica* varieties and susceptibility to pests and diseases under tropical environments. Although temperate *japonica* rice has small and very specialized markets in Southeast Asia, the demand for temperate *japonica* varieties is increasing and it has great potential for realizing higher income returns to farmers in the region.

2. Progress of Temperate *Japonica* Rice Adaptable to Tropical Regions

Facing the increasing demand for *japonica* varieties in the tropics, the Rural Development Administration (RDA) of the Korean government and International Rice Research Institute (IRRI) initiated the Germplasm Utilization Value Added (GUVA) project from 1992 in cooperation with the Philippine Rice Research Institute (PhilRice), with a budget scale of USD 150,000 every year. The aim of the GUVA project is to develop *japonica* varieties with high yield potential and desirable agronomic characteristics that are adaptable to the tropics. We used *japonica* varieties from South Korea as the starting materials for line development. However, the photosensitivity of many temperate *japonica* rice plants was the major bottleneck in the selection of suitable plant base materials for field tests. Under the short-day conditions in the tropics, many temperate *japonica* varieties typically exhibit extra-early flowering (~45 days after seeding) compared to *indica* rice plants (around 75 days after seeding) [3]. The extreme early flowering of temperate *japonica* in the tropics results in a reduced yield due to a reduction in biomass and poor panicle development. Kim et al. [4] reported that the yields of the Korean temperate *japonica* varieties showing extra-early heading in the tropical region were 0.6 to 1.4 ton/ha, while those in Korea located in the temperate region were 7 to 10 ton/ha. The interplay of flowering factors under different photoperiodic conditions limits the speed of *japonica* rice's adaptation to the tropics [5], and it was one of the main challenges of temperate *japonica* rice breeding in the tropics. The transition from the long-day conditions in the temperate areas to the short-day conditions in the tropics appeared to be the cause of stunted growth, weak tillers, small panicles, and premature headings of the temperate *japonica* rice in the tropics [5]. Fortunately, early GUVA scientists found that some *japonica* rice germplasm sources such as Jinmibyeo showed delayed heading [4] which were deployed in the GUVA breeding program.

Despite the difficulty in finding genetic materials with a suitable heading property and resistance to biotic stresses in the tropics, the very first successful breed of temperate *japonica* rice, variety MS 11 (Maligaya Special 11), was released in 2008 in the Philippines. MS 11 was the product of a cross between two Korean *japonica* varieties, Jinmibyeo, showing delayed heading under the short-day condition, and Cheolweon 46, which is a *japonica* rice resistant to diseases and pests prevalent in the Philippines. MS 11 is a semi-dwarf (90 cm) and early-maturing (112 days) variety, and has short, round-shaped grains, possessed low amylose content (15.5%), and a low gelatinization temperature, which are the typical characteristics of *japonica* rice. Multi-location trials demonstrated that MS 11 yielded an average of 4.9 ton/ha with 70% premium milling and 60% head rice recovery rates [6]. In 2009, IRRI 152 (NSIC Rc220), locally known as Japonica 1, was released in the Philippines (<https://nsic.buplant.da.gov.ph/>, accessed on 13 September 2021). This variety demonstrated attributes comparable to those of MS 11, and its yield was approximately 25% higher than that of MS 11 based on multi-location trials. In 2010, MS 11 and Japonica 1 were approved for large-scale planting by the National Seed Industry Council (NSIC) of the Philippines and officially handed to farmers of Bohol for commercial cultivation. As of 2021, four more *japonica* varieties, namely, Japonica 2 (<https://nsic.buplant.da.gov.ph/>, accessed on 13 September 2021), Japonica 6 [7], Japonica 7 [8], and Cordillera 4 [9], had been developed (Tables 1–3). These varieties were also recommended to be released in the Philippines based on the National Cooperative Test (NCT) that evaluates the yield performance, grain quality (milling traits and physical properties) and reactions to pests and diseases of candidate varieties for four consecutive seasons under multiple environments to decide whether to

accept or reject a variety. Once the varieties were developed, they were evaluated through the farmer participatory varietal selection (PVS) process as a part of the participatory technology transfer of IRRI.

Table 1. Six temperate *japonica* rice varieties developed from the GUYA project.

Variety	Release Name	IRRI Designation	Parentage	Year Registered	Reference
MS11 *	NSIC Rc 170 SR	IRRI 142	Jinmibyeo/ Cheolweon 46	2008	Jeong et al. [6]
Japonica 1	NSIC Rc 220 SR	IRRI 152	IR77863-95-2- 3/HR15490-34	2009	https://nsic.buplant.da.gov.ph/ , accessed on 13 September 2021
Japonica 2	NSIC Rc 242 SR	IRRI 157	IR80091-46-2- 1/IR71663-14-2-3-5	2011	https://nsic.buplant.da.gov.ph/ , accessed on 13 September 2021
Japonica 6	NSIC Rc 484 SR	IRRI 202	MS 11/IR86743-2B-1-4	2017	Jeong et al. [7]
Cordillera 4	NSIC Rc 566 SR	IRRI 232	Jinmibyeo/SR18977- 2-7-2-TB-1	2019	Jeong et al. [9]
Japonica 7	NSIC Rc 584 SR	IRRI 236	Japonica 2/IR11K233	2019	Jeong et al. [8]

* Local name of MS 11 in Korea is Asemi.

Table 2. Main agronomic traits of the temperate *japonica* rice varieties based on the NCT.

Variety *	Culm Length (cm)	Days to Maturity	Yield (t/ha)		Milling Recovery (%)	Eating Quality
			Variety	Check Variety **		
MS11	90	112	4.9	4.5 (IR72)	70.5	Soft
Japonica 1	89	109	2.8	2.3 (MS11)	64.7	Soft
Japonica 2	94	109	3.7	3.0 (MS11)	63.0	Soft
Japonica 6	87	121	3.6	2.6 (MS11)	73.0	Medium
Cordillera 4 ***	77	145	3.1	2.5 (PSB Rc 96)	73.0	Soft
Japonica 7	91	111	3.0	2.6 (MS11)	69.0	Soft

* All data are based on the NCT (National Cooperative Test) in the Philippines with different years/regions for each variety; ** Yield and the name of check varieties; *** NCT for Cordillera 4 was conducted in cold and elevated regions in the Philippines.

Table 3. Responses to major biotic stresses of the temperate *japonica* rice varieties based on the NCT.

Variety *	Blast	Bacterial Leaf Blight	Tungro Disease	Stem Borer	Brown Planthopper	Green Leafhopper
MS11	R **	I	I	I	S	S
Japonica 1	S	I	S	I	I	S
Japonica 2	I	I	S	MS	MS	MS
Japonica 6	I	I	S	I	S	S
Cordillera 4	I	S	S	R	I	MR
Japonica 7	I	I	S	R	I	I

* All data are based on the NCT (National Cooperative Test) in the Philippines with different years/regions for each variety; ** R—resistant; MR—moderately resistant; I—intermediate; MS—moderately susceptible; S—susceptible.

According to Kim et al. [4], the rice germplasm accessions originating from the tropical/subtropical regions harbor the non-functional alleles of *Hd1* associated with heading,

and all 12 temperate *japonica* varieties and breeding lines that were developed under the GUYA project possessed the loss-of-function alleles of *Hd1*, which are not common in temperate *japonica* varieties. A phylogenetic analysis using 2918 SNP data points revealed that the genome statuses of the 12 breeding lines were very similar to those of the Korean temperate *japonica* varieties. These results indicate that the functional *Hd1* alleles of temperate *japonica* varieties induced extremely early flowering in the tropics and the non-functional *Hd1* alleles brought about the adaptation of temperate *japonica* rice to tropical regions. Bombay et al. [5] also suggested that a non-functional *Hd1* allele was critical for the tropical adaptation of temperate *japonica* rice, since it delays the heading date, which is essential for prolonging the vegetative state and achieving optimum biomass, an increased spikelet number, and a high grain-filling capacity.

3. Breakthrough in Yield with the New Variety, Japonica 7

The initial *japonica* varieties developed under the GUYA project clearly underperformed with respect to the *indica* group in terms of yield and stability under the tropical environment compared to recent leading *indica* varieties. On the contrary, the yields of the most recent variety, Japonica 7, were observed to be similar to or higher than those of high-yielding *indica* varieties such as NSIC Rc 222 and NSIC Rc 238 in the field trials at IRRI (14.2° N, 121.2° E) and Philippine Rice Research Institute (15.3° N, 121.0° E) in the 2021 dry season (Table 4).

Table 4. Yields of temperate *japonica* rice varieties developed under the GUYA project and leading *indica* varieties in the 2021 dry season.

Variety	Ton/Ha	Yield (Rough Rice)		
		IRRI	PhilRice-CES *	
		% **	Ton/Ha	% **
MS 11	5.4	79	5.8	73
Japonica 1	6.1	90	5.3	66
Japonica 2	5.4	79	5.6	70
Japonica 6	7.1	104	6.0	75
Japonica 7	7.0	103	8.8	110
NSIC Rc 222 (<i>indica</i>) ***	6.8	100	8.0	100
NSIC Rc 238 (<i>indica</i>) ***	6.8	100	6.3	79
LSD (0.05) ****	0.6	-	1.3	-

* Central Experiment Station, Philippine Rice Research Institute located in Nueva Ecija, Philippines; ** Relative yield level when the yield of NSIC Rc 222 is considered as 100%; *** NSIC Rc 222 and NSIC Rc 238 are the leading varieties in the Philippines; **** Least significant difference.

Japonica 7 also showed intermediate reactions or resistance to bacterial leaf blight (BLB), stem borer, brown planthopper (BPH), and green leafhopper in the NCT (Table 3). Japonica 7 was regarded as susceptible to tungro disease in the NCT (Table 3); however, this variety showed moderate field resistance against tungro disease at IRRI in the 2020 wet season (Figure 1).

Figure 1. Field resistance to tungro disease of Japonica 7 in the 2020 wet season at IRRI.

As mentioned above, MS 11 and Japonica 7 showed moderate resistance to tungro disease. Rice tungro spherical virus (RTSV) is one of the viruses causing tungro disease [9]. The resistance to RTSV is associated with the allele types of the gene encoding eukaryotic translation initiation factor 4 gamma (*EIF4G*, *LOC_Os07g3690*) [10]. To examine the presence of the resistance allele of *EIF4G* in the six GUYA varieties, *EIF4G* in these varieties was partially sequenced. The partial sequences of *EIF4G* showed that MS 11 and Japonica 7 possess the resistance allele of *EIF4G* (Table 5), which is consistent with the moderate resistance to tungro disease observed in these varieties.

Table 5. Sequences of the 30-bp region (3163 to 3192) of *EIF4G* (*LOC_Os07g3690*) in the six temperate *japonica* rice varieties developed under the GUYA project and an RTSV-susceptible variety, Nipponbare.

Variety	Position in <i>EIF4G</i> (<i>LOC_Os07g3690</i>)	Allele Type
Nipponbare	3163 GCCGAAAGTCTTATGTTGTTGATCACCCA 3192	Susceptible
MS 11	GCCGTAAAGTCTTATGTTGTTGATCACCCA	Resistant
Japonica 1	GCCGAAAGTCTTATGTTGTTGATCACCCA	Susceptible
Japonica 2	GCCGAAAGTCTTATGTTGTTGATCACCCA	Susceptible
Japonica 6	GCCGAAAGTCTTATGTTGTTGATCACCCA	Susceptible
Japonica 7	GCCGTAAAGTCTTATGTTGTTGATCACCCA	Resistant
Cordillera 4	GCCGAAAGTCTTATGTTGTTGATCACCCA	Susceptible

4. Challenges and Breeding Initiatives

The heading date and yield of the GUYA *japonica* varieties are much improved, but there is still a gap in the yield of the temperate *japonica* varieties between the tropics and the temperate region. The *Ehd1* gene, encoding a B-type response regulator protein, promotes the expression of florigen genes such as *Hd3a* and *RFT1* under both short-day and long-day conditions [11]. The transfer of the non-functional allele of *Ehd1* into the GUYA varieties may delay their heading dates and enhance their yields. *GN1a* [12] and *OsSPL14/WFP* [13] control the grain number per panicle, and *SCM2* governs the grain number per panicle and strong culm [14]. The yield-related alleles of these genes, which are usually absent in temperate *japonica* varieties, need to be tested in the GUYA varieties to see their effects on yield enhancement. Whenever possible, the marker-based selection of these genes is desirable to precisely transfer only the target genes/alleles (<100 kb size) from *indica* donors to *japonica* backgrounds to keep the original characteristics of the elite *japonica* varieties and to avoid undesired traits in the final breeding products such as poor fertility.

Besides the traits for the heading date and yield, the development of temperate *japonica* rice in the tropics requires the improvement of disease and pest resistance and grain quality. Enhancing the tolerance to pests and diseases in new varieties is one of the fundamental

goals of the current breeding program for temperate *japonica* rice in the tropics. Among various biotic stresses, BPH, BLB, tungro, and blast are the most common that hamper the growth performance of temperate *japonica* varieties under the tropical environment. Genes associated with resistance to blast (*Pita*), BLB (*xa5*), and BPH (*BPH32*) were already incorporated into high-yielding *indica* varieties such as NSIC Rc 222 and NSIC Rc 238 (Table 6). The SNP-based allele typing of these three resistance genes in the six released GUYA *japonica* varieties showed out that none of the six varieties have these resistance genes (Table 6).

Table 6. Allele types for some of biotic-stress-resistance genes for six temperate *japonica* rice varieties developed from the GUYA project.

Variety	Allele Type of Resistance Gene *		
	Blast (<i>Pita</i>)	BLB (<i>xa5</i>)	BPH (<i>BPH32</i>)
MS 11	S	S	S
Japonica 1	S	S	S
Japonica 2	S	S	S
Japonica 6	S	S	S
Japonica 7	S	S	S
Cordillera 4	S	S	S
NSIC Rc 222 (<i>indica</i>) **	R	R	R
NSIC Rc 238 (<i>indica</i>) **	R	R	R

* R—resistant allele type; S—susceptible allele type; ** NSIC Rc 222 and NSIC Rc 238 are two of the leading varieties in the Philippines.

The genotypic screening of 181 rice germplasm accessions revealed that only 4.1% of *japonica* accessions harbor the resistance allele type of *Pita*, whereas 83.5% of *indica* accessions have the resistance allele (Table 7). The frequencies of the resistance allele types for *xa5* and *BPH 32* in temperate *japonica* and *indica* were similar to those for *Pita* (Table 7). These results suggest that many temperate *japonica* rice plants, which have been mostly cultivated in the temperate region, do not harbor important genes necessary to adapt to the tropical region. To develop disease- and insect-resistant *japonica* varieties for the tropics, the resistance alleles of these genes should be incorporated into future *japonica* breeding lines through the marker-assisted selection (MAS) of the resistance alleles and precise bioassays for the target pests and diseases.

Table 7. Number (percentage) of *japonica* and *indica* rice accessions harboring the resistance alleles of *Pita*, *xa5*, and *BPH32* among 181 rice germplasm accessions.

Subspecies	Number (Percentage) of Rice Accessions Harboring Resistance Allele Type		
	Blast (<i>Pita</i>)	BLB (<i>xa5</i>)	BPH (<i>BPH32</i>)
<i>Japonica</i> (96)	4 (4.1%)	6 (6.3%)	3 (3.1%)
	Dongjinbyeo,	IR13K158, IR13K176	IR13K187, IR18K1018
	IR13K187	IR13K177, IR13K181	IR18K1028
	IR18K1018, IR18K1028	IR13K187, IR18K1018	
<i>Indica</i> (85)	71 (83.5%)	29 (34.1%)	52 (61.1%)

Under the tropical environment, the grains of many temperate *japonica* germplasm accessions and many of our current temperate *japonica* breeding lines are prone to pre-harvest sprouting (PHS) and have short seed longevity and poor grain quality such as in exhibiting grain breakage and grain chalkiness under tropical climate conditions, especially during the wet season [15,16] (Figure 2). Overcoming these limitations is critical because these usually cause significant reductions in grain quality and yield.

Figure 2. Inferior grain quality of temperate *japonica* rice under the tropical climate. (A) Pre-harvest sprouting, (B) short seed longevity, and (C) cracked milled rice.

PHS, the germination of seeds on panicles prior to harvest, often occurs under warm and humid weather conditions and due to unexpected weather events such as typhoons at the seed-maturity stage [17–19]. As compared with *indica* rice widely grown in the tropical region, temperate *japonica* rice varieties have adapted to cool and dry environments during the seed-ripening period; hence, they are vulnerable to PHS when cultivated under tropical climate conditions. Lee et al. [15] screened 48 *japonica* varieties cultivated in the temperate regions—California in the United States, Japan, and the Republic of Korea—and the mean PHS resistance of these *japonica* varieties was 39%, whereas the control group composed of 24 *indica* varieties showed outstanding resistance, with a mean of 93%. The *Sdr4* locus on chromosome 7 involved in flavonoid biosynthesis and abscisic acid signaling pathways is responsible for the strong PHS resistance in *indica* rice varieties [20,21]. *Japonica*-derived loci on chromosome 1 and 4 associated with PHS resistance are related to plant-hormone-mediated signaling pathways [15]. Breeding efforts to introgress the PHS-resistance loci into elite temperate *japonica* varieties are underway.

Seed longevity is a key trait for securing farmers' seed lots under hot and humid weather [22]. The loss of seed viability and vigor, especially under rapid climate change, leads to poor crop establishment and a low yield as well as reduced eating quality, which often result in serious economic losses. It is therefore necessary to improve the seed longevity of the GUYA lines using *indica* or aus resources having relatively high seed longevity [16,23–25]. Sasaki et al. [26] reported that *TPP7*, encoding a trehalose-6-phosphate phosphatase, in the *qLG-9* locus on chromosome 9 controls the seed longevity of temperate *japonica* × *indica* rice near isogenic lines. Other seed-longevity genes identified through a genome-wide association analysis using the *indica* and *aus* rice panels from the 3000 Rice Genomes Project [27] are related to DNA repair and transcription, sugar metabolism and reactive-oxygen-species scavenging [28,29].

The head rice yield is the percentage of intact grains obtained from rough rice after the milling process. The head rice yield directly affects the income of rice farmers because the price of whole-grain rice is typically several times higher than that of broken grains. Rice milling is a multi-step process that includes hulling, milling, and separating whole kernels from broken ones. The cracking of rice kernels (or kernel fissuring) is one of the major problems in producing temperate *japonica* rice under the tropics. It reduces the market value, increases the ratio of broken rice during milling and cooking, and diminishes flavor [30]. Cracking often follows harvest delays due to unstable weather, heavy rain, or high air temperatures [31,32]. Several QTLs associated with kernel-cracking resistance were identified in *japonica* rice [33,34], *indica* rice [35], and wild rice [30]. DNA markers linked to QTLs associated with kernel-cracking resistance would facilitate the efficient selection

of *japonica* rice breeding lines with kernel-cracking resistance without being significantly affected by harvesting and milling conditions.

5. Conclusions and Future Work

The goal of our endeavor described here is to develop temperate *japonica* varieties adapted to the tropical environment. The outcomes of our efforts not only can widen the potential market into which farmers in the tropical regions could tap, but also will provide competent genetic resources of temperate *japonica* rice ready for any drastic consequences of global warming. For the last 29 years, we have delivered six released varieties, which expanded the cultivation area for temperate *japonica* to tropical regions by introducing the non-functional allele of the *Hd1* gene and resistance against some of the major diseases and pests to ensure high yield stability in the tropics.

Despite having overcome some of the prevalent problems encountered with temperate *japonica* rice in the tropical environment, temperate *japonica* varieties remain less popular in Southeast Asian countries. For now, the cultivation of *japonica* rice cultivars is still very limited. Furthermore, our initial varieties such as MS 11 or Japonica 1 are mostly cultivated in the region. Information on the performance of our recent cultivars in farmers' fields is still lacking. This is most probably due to multi-faceted problems associated with seed dissemination to seed producers and farmers, little access to more comprehensive data for the recent high-yielding varieties such as Japonica 7, and the grain quality of temperate *japonica* varieties that may not meet farmers' preferences.

In addition, the following concerns still need to be addressed for the further development of temperate *japonica* varieties adaptable to the tropics: (1) enhancing yields in the wet season; (2) introducing resistance to biotic and abiotic stresses; and (3) improving grain quality by alleviating PHS, short seed longevity, and grain breakage.

Our future work will focus more on highly efficient molecular breeding based on accurate genetic information on high-impact QTLs/genes for yield stability and potential, enhanced resistance to biotic and abiotic stresses, and high grain quality in order to develop superior *japonica* rice varieties with improved adoption and enhanced genetic gain in tropical regions. This will be achieved by combining the conventional breeding process and new breeding tools such as trait genotyping for improved parental selection, marker- and genomics-assisted breeding, and speed breeding.

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