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# Current Scenario of Breeding Approaches in Rice

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## Abstract

Rice is the predominant crop in India and is the staple food in eastern and southern Indian populations. One of the oldest grown crops is rice. The initial discovery of cytoplasmic male sterile (CMS) three-line system made it possible to produce hybrids that significantly increase rice yields compared to its inbred counterparts. Further genetic and molecular studies help elucidate the mechanisms involved in CMS male sterility. Additional CMS types were also discovered with similar genetic control from wild sources by interspecific hybridization. In India more than 1200 varieties were released for cultivation suitable different ecosystems and out of them 128 varieties have been contributed from NRRI, Cuttack. A list of these varieties are furnished below with their duration, grain type, yield potential, reaction to major disease and insects grain quality and tolerance to different adverse situations. Recent advances in molecular approaches used in modern rice breeding include molecular marker technology and marker-assisted selection (MAS); molecular mapping of genes and QTLs and production of hybrids and alien introgression lines (AILs). Genomic selection (GS) has been projected as alternative to conventional MAS. GS has huge potential to enhance breeding efficiency by increasing gain per selection per unit time. Due to the adaptation of semi dwarf high yielding varieties, combined with intensive input management practices, the country witnessed an impressive rice production growth in the post-independent period. Rice production was increased four times, productivity three times while the area increase was only one and half times during this period. The projected rice requirement by 2025, in order to keep up with increasing population, is about 130 m.t. The challenge of growing rice production is made more difficult by declining trends in HYV's yields, decreasing and degrading natural resources such as land and water and a severe labour shortage.

**Keywords:** Rice, Hybrid, Heterosis, Marker Assisted Selection, Genomic Selection

## 1. Introduction

Rice (*Oryza sativa* L.) is one of the most important staple foods that feed more than half of the world's population; Asia and Africa are the major consuming regions [1]. For at least half of the world's population, rice is the most significant source of calories. As a result, many countries have developed strategies to achieve rice self-sufficiency by growing the area under cultivation or increasing yield per

unit area. In case of rice, however, grain quality is just as critical as yield. Heterosis is the ability of  $F_1$  offspring to outperform either parent and it is the only way to achieve full hybrid vigor in crop plants. For decades, this has been a factor in the production of superior cultivars for many crops in agriculture and enthusiastic geneticists [2]. In a hybrid compared to HYVs, the appropriate combination and manipulation have produced benefits [3]. Since the discovery and growth of the cytoplasmic male sterile (CMS) source in the middle of the twentieth century, heterosis was possible due to its self-pollinating existence (0.3–3.0% outcrossing). Nanyou 2, the first indica rice hybrid, was released for cultivation in China in 1974.

Subsequently, relatively heterotical hybrid rice (HR) breeding approaches were adopted, such as two-line system and super hybrids, which complemented Chinese food security and living standards significantly in India. In 1989, the Indian Council of Agricultural Research (ICAR) launched a special goal-oriented and time-bound project for rice called “Promotion of Research and Development Efforts on Hybrids in Selected Crops,” which included 12 network centres. Around four years of intensive research (1989–1993) paid off handsomely, and India became the second country after China to grow and commercialize hybrid rice. APRRI, Maruteru, launched the first hybrid variety APRH-1 in 1993–1994 for Andhra Pradesh. So far, 117 rice hybrids (36 from public organization and 81 from private sector) have been produced, with duration ranging from 115 to 150 days and a total area of 3.0 mha, accounting for 7.0 percent of India’s total rice acreage [4]. As a result, breeding for consumer-favored grain qualities has become a major target for breeding programs all over the world. Grain quality must be clearly identified and the genes underlying their regulation deciphered before it is possible to breeder for fastidious customer preference. Rice is a staple food crop that accounts for more than a fifth of all calories consumed by humans [5]. Since rice is the most common cereal crop in most Asian countries and is the staple food for more than half of the world’s population, even a small increase in rice grain micronutrient content could have a major effect on human health. Hybrid rice is the product of a cross between two rice parents with genetically different traits. When the right parents are chosen, the hybrid can outperform both parents in terms of vigor and yield. Higher yields, increased vigor, and increased resistance to diseases and insect resistance are all advantages of hybrid rice [6].

## 2. Hybrid rice breeding program in India

Rice is the predominant crop in India and is the staple food in eastern and southern Indian populations. One of the oldest grown crops is rice. The two cultivated species of rice are (i) *Oryza sativa* - Asian rice Cultivated Species of Rice (A) Asian Rice (*Oryza sativa* L.). It is predominant species which has spread to different part of world. (B) African Rice (*Oryza glaberrima* L.) [7]. It’s also only found in Africa’s tropical region. Based on morphological and physiological characteristics as well as geographical adaptation, Asian rice is divided into three ecological forms. 1. *Indica*: Grown in tropical climate such as India, Sri- Lanka, China, Thailand, Malaysia, Taiwan 2. *Japonica*: Japan and Korea have a temperate climate 3. *Javanica*: Indonesian hybrid of Indica and Japonica (**Table 1**).

## 3. IRRI’s hybrid rice program

Germplasm, parents and hybrids are being developed through new breeding and seed technology by researcher. Currently scientists are working for the hybrids rice production with the Collaboration of NARS and private sectors.

S.No.	Year	Remarks
1	1926	Heterosis in rice reported
2	1964	China started hybrid rice research
3	1970	China discovered a commercially usable genetic tool for hybrid rice (male sterility in a wild rice = Wild Abortive)
4	1973	PTGMS rice was found in China
5	1974	First commercial three-line rice hybrid released in China
6	1976	Large scale hybrid rice commercialization began in China
7	1979	IRRI revived research on hybrid rice
8	1981	PTGMS rice genetics and application was confirmed
9	1982	Yield superiority of rice hybrids in the tropics confirmed (IRRI)
10	1990s	- India and Vietnam started hybrid rice programs with IRRI
11	1991	More than 50% of China rice land planted to hybrids
12	1994	First commercial two-line rice hybrid released in China
13	1994–1998	Commercial rice hybrids released in India, Philippines Vietnam

**Table 1.**  
Brief history of hybrid rice.

#### 4. Wild species

The genus *Oryza* contains twenty valid species, two of which are cultivated, namely *Oryza sativa* and *Oryza glaberrima*. There are nine diploid species among the remaining 18 species (Table 2). Six of them are tetraploid. Some of the wild species utilized in breeding programme are *Oryza perennis* - Co 31 GEB 24 x *O. perennis* [8–10].

#### 5. Breeding component and system in hybrid rice development

For breeding technique, there are three approaches (1) the three-line method also known as CMS (cytoplasmic male sterility) system (2) the two-line method also known as the PTGMS (photo/temperature sensitive genic male sterility) system and (3) the one-line method, also known as the apomixis system. Inter-varietal hybrids, Inter-sub-specific hybrids and inter-specific or intergeneric hybrids are three ways to increase the degree of heterosis (Table 3).

##### 5.1 Two-line hybrid rice

The two-line hybrid rice research began in China and was successfully scaled up in 1995. The thermo-sensitive male sterile lines (TGMS) lines are those whose sterility expression is regulated by temperature, whereas photoperiod-sensitive male sterile (PGMS) lines are those whose expression is controlled by day-length duration. Backcrossing has successfully transferred the PGMS trait to many *Indica* and *Japonica* rice cultivars in China. In China, rice hybrids produced by this male sterile system are being tested in multiple locations. The degree of heterosis in two-line hybrid rice is close to that of three-line hybrid rice, but the technique methods is different. Unlike three-line hybrids, the male parent of two-line hybrid is not limited by restorer genes, allowing us to use both good restorer lines with high combining potential and good traditional varieties without restorer genes as male

Botanical Name	Chromosome No.	Genome	Origin
<i>O. sativa</i>	24	AA	Asia
<i>O. nivara</i>	24	AA	Asia
<i>O. meridionalis</i>	24	—	- Australia
<i>O. longistaminata</i>	24	AA	Africa
<i>O. rufipogon</i>	24	AA	Asia
<i>O. glumaepatula</i>	24	—	America
<i>O. grandiglumis</i>	48	CCDD	America
<i>O. glaberrima</i>	24	AA	Africa
<i>O. barthii</i>	24	AA	Africa
<i>O. australiensis</i>	24	EE	Australia
<i>O. latifolia</i>	48	CCDD	America
<i>O. alata</i>	48	CCDD	America
<i>O. eichingeri</i>	24, 48	CC, BBCC	Africa
<i>O. minuta</i>	48	BBCC	Asia
<i>O. punctata</i>	48	BBCC	Asia
<i>O. officinalis</i>	24	CC	Asia
<i>O. granulata</i>	24	—	Asia
<i>O. meyeriane</i>	24	—	Asia
<i>O. ridleyi</i>	48	—	Asia
<i>O. longiglumis</i>	48	—	New Guninea
<i>O. brachantha</i>	24	FF	Africa
<i>O. schlechter</i>	—	—	New Guninea

**Table 2.**  
*Wild species of Rice.*

parents. Since restorer genes are not limited, there's a better chance of breeding elite hybrids [12]. The developed PTGMS lines such as PA64S, GZ63S, Zhun S, etc. have many advantages for hybrid combinations, such as larger freedom for crossing, higher yielding, better quality and diseases resistance. The yield of improved two-line hybrid rice combinations is usually higher than of three-line hybrids used as controls. Meanwhile, seed processing and cultivation techniques for two-line hybrids have advanced to the point that they can be used in commercial production. Breeding of elite restorer lines is the key for matching heterotic combinations [13] (Table 4).

5.2 Three-line system hybrid rice

5.2.1 Identification and utilization of cytoplasm male sterility

The role of rice cytoplasm in male sterility was first discovered in 1954 [16]. They studied cytoplasmic differences among rice varieties in 1965 and formed a male sterile line for the first time by transferring the nuclear genotype of rice cultivar Fujisaka [17]. However, due to its instability, poor plant form and photoperiod sensitivity, this cytoplasm male sterility (CMS) line could not be used to breed rice. Yuan Long Ping proposed the concept of using heterosis in rice in 1964, and for the



Sl. No.	Rice Hybrids	Year of Release	Duration	Developed by	Recommended for
1	DRRH- 3	2010	131	DRR, Hyderabad	Andhra Pradesh, Gujarat, Madhya Pradesh, Odisha, Uttar Pradesh
2	US - 312	2010	125–130	Seed Works International, Hyderabad.	Andhra Pradesh, Bihar, Karnataka, Tamil Nadu, Uttar Pradesh, West Bengal.
3	CRHR-32	2010	125	CRRI, Cuttack, Odisha	Bihar, Gujarat.
4	INDAM 200–017 (IET 20419)	2011	120–125	Indo-American seeds, Hyderabad	Odisha, Chhattisgarh, Gujarat Maharashtra, Andhra Pradesh.
5	27P11	2011	115–120	PHI Seeds (P) Ltd.	Karnataka, Maharashtra.
6	VNR 2245 (VNR-204)	2011	90–95	VNR Seeds Pvt. Ltd., Raipur	Chhattisgarh, Tamil Nadu.
7	VNR 2245 (VNR-202)	2011	100–105	VNR Seeds Pvt. Ltd., Raipur	Uttar Pradesh, Uttarakhand, West Bengal, Maharashtra, Tamil Nadu.
8	Shyadri-5 (Hybrid)	2011	110–115	RARS, Karjat (BSKKV)	Konkan Region of Maharashtra.
9	CO (R) H-4	2011	130–135	TNAU, Coimbatore	Tamil Nadu.
10	Hybrid CO 4	2012	130–135	TNAU, Coimbatore	Tamil Nadu.
11	US 382	2012	125–130	Seed Works International Pvt. Ltd., Hyderabad	Tripura, Madhya Pradesh, Karnataka.
12	27P31	2012	125–130	PHI Seeds Pvt. Ltd. Hyderabad	Jharkhand, Maharashtra, Karnataka, Tamil Nadu, Uttar Pradesh, Bihar, Chhattisgarh.
13	27P61	2012	132	PHI Seeds Pvt. Ltd. Hyderabad	Chhattisgarh, Gujarat, Andhra Pradesh, Karnataka, Tamil Nadu.
14	25P25	2012	110	PHI Seeds Pvt. Ltd. Hyderabad	Uttarakhand, Jharkhand, Karnataka.
15	Arize Tej (HRI 169)	2012	125	Bayer Bio Science Pvt. Ltd., Hyderabad	Bihar, Chhattisgarh, Gujarat, Andhra Pradesh, Tamil Nadu.
16	PNPH 24	2012	120–130	Nuziveedu Seeds Limited, A.P.	Bihar, West Bengal, Odisha.
17	PNPH 924–1	2012	125–135	Nuziveedu Seeds Limited, A.P.	West Bengal, Assam
18	NK 5251	2012	NA	NA	Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra, Gujarat.

Sl. No.	Rice Hybrids	Year of Release	Duration	Developed by	Recommended for
19	VNR 2245	2012	120–125	VNR Seeds Pvt. Ltd., Raipur	Chhattisgarh, Tamil Nadu.
20	VNR 2355 Plus	2012	130–135	VNR Seeds Pvt. Ltd., Raipur	Uttar Pradesh, Uttarakhand, West Bengal, Maharashtra, Tamil Nadu.
21	CR Dhan 701	2012	140–145	NA	Bihar, Gujarat.
22	JKRH 3333	2013	135–140	JK Agri Genetics Ltd., Hyderabad- 16.	West Bengal, Bihar, Chhattisgarh, Gujarat, Andhra Pradesh.
23	RH- 1531	2013	118–125	Devgen Seeds & Crop Technology, Hyderabad	Major Hybrid rice growing regions (Madhya Pradesh, Uttar Pradesh, Andhra Pradesh, Karnataka, Maharashtra).
24	CO 4 (IET 21449)	2013	NA	TNAU, Coimbatore	Tamil Nadu, Gujarat, Maharashtra, Uttarakhand, Uttar Pradesh, Bihar, Chhattisgarh, West Bengal.
25	Arize Dhani	2013	NA	Bayer Bio-Science, Hyderabad	Odisha.
26	27P52	2013	NA	PHI Seeds Pvt. Ltd. Hyderabad- 82.	Andhra Pradesh, Chhattisgarh, Gujarat, Odisha, Uttarakhand.
27	27P63	2013	NA	PHI Seeds Pvt. Ltd. Hyderabad- 82.	Andhra Pradesh, Chhattisgarh, Karnataka, Uttar Pradesh.
28	KPH - 199	2013	NA	Kaveri Seed Company Limited, Secunderabad	Andhra Pradesh, Chhattisgarh, Madhya Pradesh.
29	KPH - 371	2013	NA	Kaveri Seed Company Limited, Secunderabad	Chhattisgarh, Jharkhand, Karnataka, Kerala.
30	VNR 2375 PLUS	2013	NA	VNR Seeds Pvt. Ltd., Raipur	Bihar, Karnataka, Punjab, Maharashtra, Uttarakhand.
31	US 305	2013	NA	Seed Works International Pvt. Ltd., Hyderabad	Andhra Pradesh, Tamil Nadu, Maharashtra.
32	US 314	2013	NA	Seed Works International Pvt. Ltd., Hyderabad	Andhra Pradesh, Bihar, West Bengal, Uttarakhand.
33	Ankur 7434	2014	NA	Ankur seed Pvt. Ltd.	Chhattisgarh.
34	PAC 807	2014	NA	Advanta India Ltd. Hyderabad	Chhattisgarh.
35	PAC 801	2014	NA	Advanta India Ltd. Hyderabad	Uttar Pradesh.

Sl. No.	Rice Hybrids	Year of Release	Duration	Developed by	Recommended for
36	CSR 43	2014	NA	—	Uttar Pradesh.
37	JKRH-401	2014	NA	JK Agri Genetics Ltd., Hyderabad- 16.	Uttar Pradesh.
38	Arize 6444 Gold	2015	130–135	Bayer Crop Science, Hyderabad	Assam, Chhattisgarh, Odisha, Uttar Pradesh, Bihar Meghalaya, Karnataka, Tamil Nadu.
39	SAVA 127	2015	115–120	Savannah seed Pvt. Ltd.	Uttar Pradesh.
40	Arize Tej (HRI 169)	2015	120	Bayer Crop Science, Hyderabad	Bihar, Chhattisgarh, Gujarat, Andhra Pradesh, Tamil Nadu, Jharkhand.
41	27P31	2015	NA	PHI Seeds Pvt. Ltd. Hyderabad- 82.	Jharkhand, Maharashtra, Karnataka, Tamil Nadu, Uttar Pradesh, Bihar, Chhattisgarh, Madhya Pradesh, Odisha.
42	PAC 801	2015	NA	Advanta India Ltd., Hyderabad	Uttar Pradesh, Jharkhand.
43	NK 16520	2016	132	Syngenta India Ltd., Secundrabad	Chhattisgarh, Uttar Pradesh, Bihar, Jharkhand, Odisha, Telangana.
44	KPH 467	2016	126	Kaveri Seed Company Limited	Chhattisgarh, Madhya Pradesh, Maharashtra.
45	KPH 272	2016	126	Kaveri Seed Company Limited	Telangana, Karnataka, Tamil Nadu.
46	37P22	2017	126	PHI Seeds Pvt. Ltd. Hyderabad	Punjab, Haryana.
47	GK 5022	2017	123 (Aerobic)	Ganga Kaveri Seeds Pvt. Ltd., Hyderabad	Bihar, Chhattisgarh.
48	27P36	2017	NA	PHI Seeds Pvt. Ltd. Hyderabad	Bihar, Madhya Pradesh, Jharkhand.
49	NPH 8899	2017	168 (Boro)	Kaveri Seed Company Limited	Uttar Pradesh, Bihar, Assam.

NA = Not available.  
Source: [11].

**Table 3.**  
*List of hybrid Rice released/notified in India during 2010–2017.*

first time in China, hybrid rice research was started. The discovery of WA, a nation-wide cooperative program was immediately established to extensively testcross with the WA and screen for its maintainers and restorers. Soon in 1972, the first group of CMS lines such as Erjiunan 1A, Zhenshan 97A and V20A were developed all using WA as the donor of male sterile genes and all using successive backcrossing method. In 1973, the first group of restorer lines such as Taiyin 1, IR24 and IR661 were screened using direct test crossing system. Nanyou 2 and Nanyou 3 hybrids



Sl. No.	Variety	Ecology	Year of release	Duration	Grain type	Recommended for
1	Phalguni	Irrigated	2010	117	LS	Odisha
2	Reeta (CR Dhan 401)	Shallow low land	2010	150	MS	Odisha
3	Luna Suvarna (CR Dhan 403)	Coastal Saline	2010	150	MS	Odisha
4	Luna Sampad (CR Dhan 402)	Coastal Saline	2010	140	SB	Odisha
5	Nua Chinikamini (Aromatic)	Shallow low land	2010	145–150	SB	Odisha
6	CR Dhan 501	Semi-deep	2010	152	LB	UP, Assam
7	CR Dhan 701	Shallow low land	2010	142	MS	Bihar, Gujarat, Odisha
8	CR Dhan 601	Boro	2010	160	MS	Orissa, WB and Assam
9	CR Dhan 500	Deep Water	2011	160	MS	Odisha, UP
10	Satyabhama (CR Dhan 100)	Upland	2012	110	MS	Odisha
11	Pyari (CR Dhan 200)	Aerobic	2012	115–120	SB	Odisha
12	Hue (CR Dhan 301)	Irrigated	2012	135	LS	Odisha
13	Improved Lalat	Irrigated	2012	130	LS	Odisha
14	Improved Tapaswini	Irrigated	2012	130	SB	Odisha
15	Sumit (CR Dhan 404)	Shallow lowlands	2012	145	LB	Odisha
16	Poorna Bhog (CR Dhan 902)	Shallow lowlands	2012	140	LS	Odisha
17	Jalamani (CR Dhan 503)	Deep Water	2012	160	MS	Odisha
18	Jayanti Dhan (CR Dhan 502)	Deep Water	2012	160	MS	Odisha
19	Luna Barial (CR Dhan 406)	Coastal Saline	2012	150	SB	Odisha
20	Luna Sankhi (CR Dhan 405)	Coastal Saline	2012	110	MS	Odisha
21	CR Dhan 907 (Aromatic)	Irrigated Late	2013	150	MS	Chhattisgarh, Odisha, Andhra Pradesh, Gujarat
22	CR Dhan 300	Irrigated	2013	140	LS	Maharashtra Gujarat Odisha, Bhar
23	CR Dhan 303	Irrigated	2014	125	SB	MP, UP, Odisha
24	CR Dhan 305	Irrigated	2014	125	SB	Jharkhand, Maharashtra and Andhra Pradesh

Sl. No.	Variety	Ecology	Year of release	Duration	Grain type	Recommended for
25	CR Dhan 304	Irrigated	2014	130	SB	Odisha and West Bengal
26	CR Dhan 201	Aerobic	2014	118	LS	Chhattisgarh and Bihar
27	CR Dhan 202	Aerobic	2014	115	LB	Jharkhand and Odisha
28	CR Dhan 407	Rainfed shallow lowland	2014	150	LB	Odisha and West Bengal
29	CR Dhan 505	Deep water	2014	162	MS	Odisha and Assam
30	CR Dhan 204	Aerobic	2014	120	LB	Jharkhand and Tamil Nadu
31	CR Dhan 306 (IET 22084)	Irrigated	2014	120–125	SB	Madhya Pradesh, Bihar, Puducherry
32	CR Dhan 205 (IET 22737)	Aerobic	2014	110	SB	Tamil Nadu, Gujarat, Odisha, Madhya Pradesh, Punjab
33	CR Dhan 101 (Ankit)	Upland	2014	110	MS	Odisha
34	CR Dhan 203 (Sachala)	Aerobic	2014	110	LS	Odisha
35	CR Dhan 206 (Gopinath)	Aerobic	2014	115	SB	Odisha
36	CR Dhan 307 (Maudamani)	Irrigated	2014	135	SB	Odisha
37	CR Dhan 408 (Chaka Akhi)	Shallow lowland	2014	165 PS	LB	Odisha
38	CR Dhan 310	Irrigated	2015	125	MS	Odisha, Madhya Pradesh and Uttar Pradesh.
39	CR Dhan 207 (Srimati)	Aerobic	2016	110–115	MS	Odisha
40	CR Dhan 209 (Priya)	Aerobic	2016	112–115	LS	Odisha
41	CR Dhan 409 (Pradhan Dhan)	Semi-deep	2016	160–165	LS	Odisha
42	CR Dhan 507 (Prasant)	Deep Water	2016	160	MS	Odisha
43	CR Dhan 800	Shallow lowland	2016	140	MS	Odisha
44	CR Sugandh Dhan 910 (Aromatic)	Irrigated Late	2016	142–145	MS	Odisha
45	CR Dhan 311 (Mukul)	Irrigated	2016	120–126	LB	Odisha

Sl. No.	Variety	Ecology	Year of release	Duration	Grain type	Recommended for
46	CR Dhan 508	Deep Water	2017	187	LB	Odisha, West Bengal, Assam
47	CR Dhan 506	Semi-deep	2017	165	MS	Assam, Andhra Pradesh and Karnataka.
48	CR Sugandh Dhan 908 (Aromatic)	Irrigated Late	2017	145	MS	Odisha, West Bengal and Uttar Pradesh
49	CR Sugandh Dhan 909 (Aromatic)	Irrigated Late	2017	140	MS	Assam, Bihar, UP, Maharashtra
50	Gangavati Ageti (Aromatic)	Upland	2017	85	LS	Karnataka
51	Purna	Upland	2017	90	SB	Gujarat
52	CR Dhan 309	Irrigated	2019	115	LS	Assam, Chhatisgarh, Uttar Pradesh
53	CR Dhan 801	Shallow lowland(for submergence and drought prone areas)	2019	140	SB	AP, Telengana, Odisha, UP and WB
54	CR Dhan 802 (Subhas)	Shallow lowland(for submergence and drought prone areas)	2019	142	SB	Bihar, Madhya Pradesh
55	CR Dhan 510	Semi-deep	2019	160	SB	WB and Odisha
56	CR Dhan 511	Semi-deep	2019	160	SB	West Bengal, Odisha
57	CR Dhan 312	Irrigated	2019	135–140	MS	Maharashtra and Chhattisgarh
58	CR Dhan 102 (Santha Bhima)	Upland	2019	105–110	SB	Odisha
59	CR Dhan 210 (Sarumina)	Aerobic	2019	110–115	LS	Odisha
60	CR Dhan 410 (Mahamani)	Rainfed shallow lowlands	2019	160–165	LS	Odisha

Source: ICAR-NRRI [14, 15].  
Grain: LS: Long Slender, MB: Medium Bold, MS: Medium Slender, SB: Short Bold, MB: Medium Bold.

**Table 4.**  
*Rice varieties developed by ICAR-NRRI, Cuttack during 2010–2019.*

with high heterosis were published in 1974 [18–20]. In another word, the discovery of WA led to successful breakthrough in hybrid rice production, resulting in the establishment of three-line hybrid rice system. As a result, China became the first country in the world to commercialize hybrid rice for food production. For commercial rice hybrids processing, a three-line hybrid system with the CMS line (A), maintainer line (B) and restorer line (R) is used. The A line cannot produce viable pollen due to the interaction between cytoplasmic and nuclear genes, so called

cytoplasmic male sterile, which anthers are pale or white and shriveled. The A line is also known as the CMS line and the seed parent because it is used as a female parent for hybrid seed development. Since the CMS line is male sterile, it cannot replicate itself and requires the assistance of a maintainer. The B line is the maintainer line, and its morphology is very similar to that of its CMS line, with the exception of its reproductive feature. However, the B line has viable pollen grains and normal seed setting, it may pollinate the A line, resulting in male sterile F1 plants. In this way, the male sterility of the A line is maintained, and the A line can be reproduced for further use or commercial purposes. Similarly, the R line will pollinate the A line because it has viable pollen grains and normal seed setting. Unlike the pollination with the B line, the F1 plants from the pollination with R line are extremely fertile, or the male sterility of the A line is restored into fertility in their progeny by R line. As a result, the R line is often referred to as the pollen parent or restoring line [21–25].

## **6. Genetic mechanism of rice heterosis**

Heterosis, also known as hybrid vigor, is the phenomenon in which progeny of diverse inbred varieties outperform both parents in terms of yield, panicle size, and number of spikelets per panicle, number of productive tillers, stress tolerance and other factors. This phenomenon has been extensively exploited in crop production as a powerful force in plant evolution. After the successful development of hybrid maize in 1930, other crop breeders, including rice breeders, were inspired to use the concept of hybrid production by exploiting heterosis. In fact, the exploitation of heterosis has been the most practical achievement of genetics and plant breeding research [26]. The impact of this phenomenon can be judged by the fact that the number of grains per square meter in rice varies significantly between (1) wild ancestors with just a few hundred (2) improved inbred varieties with about 40,000, and (3) rice hybrids with about 52,000. Rice heterosis was first reported by Jones (1926) who observed that some F1 hybrids had more culms and greater yield than their parents. Between 1962 and 1967, a variety of proposal came from around the world for commercial exploitation of heterosis to become a major component of national and international rice improvement programs. Rice breeders from Japan, China, United States, India, the former Soviet Union and Philippines, for example, began working on projects to use rice heterosis. However, progress had been hampered by rice's inability to be strictly self-pollinated crop, as opposed to corn which is needed for hybrid seed development, extremely difficult [27–29].

## **7. Molecular technique to enhance rice breeding activities**

Recent progress in molecular biology and biotechnology increases opportunities to use rice genetic tools not addressed in previous programs for rice production. The availability of genomic, phenotypic, geographical, and ecological information among other sequence data, when analyzed together, enables researchers to strategically plan experiments based on established models predicting plant performance [3, 30]. Molecular marker technology and marker-assisted selection (MAS), molecular mapping of genes and QTLs and the generation of hybrids and alien introgression lines [31–34] are just a few of the molecular approaches used in modern rice breeding. MAS is a form of genomic assisted breeding that uses molecular markers to map QTLs or unique genes linked to phenotypes or target traits in order to select individuals with desirable alleles for desired traits [32]. MAS

has many benefits over traditional phenotypic selection, including the fact that it is easier than phenotypic screening, that selection can be performed at the seedling level, and that a single plant can be selected based on its genotype [35].

Breeding for improved grain is complex because many of the quality traits are phenotyped using subjective and or expensive biochemical methods. As a result, scientists have been able to map/clone several QTLs/genes for various quality traits and developed molecular markers to aid in grain quality selection. Co-dominant marker, making it ideal for marker-assisted backcrossing for recessive trait like aroma, since lines carrying the aroma gene can be selected in the heterozygote state without having to screen progeny [36, 37]. Other researchers have produced markers for the 8-bp deletion in exon 7 of chromosome 8. Other alleles in the BADH2 gene, such as a 7-bp deletion in exon 2 [38–40] and a 3-bp insertion in exon 13 found in aromatic rice varieties from Myanmar [41], have also been functionally identified. Around the world, functional markers for RM 190, a waxy gene SSR and waxy SNPS on intron (In1), exon 6 (Ex6) and exon 10 (Ex10) are used to select for AAC and RVA around the world [42]. The waxy SNP haplotypes have been found to be more effective in selecting for AAC and RVA than the RM 190 haplotype across these three SNPs in the waxy genome [43–47].

## 8. Outstanding elite hybrid rice varieties in India

In India many varieties of rice have been released by Indian Council of Agriculture Research (ICAR) institute, state agricultural universities and private seed companies.

## 9. Future trends in rice breeding

Rice production would have to double by 2050 to keep up with population growth. If the world's population grows, so will consumers demands for higher-quality rice. In addition to this challenge, climate change is combining new biotic and abiotic stresses. As a result, when designing new lines, rice breeders must consider a large number of simple and quantitative traits in combination while preserving and enhancing grain quality. MAS has been effective in improving certain biotic, abiotic and quality traits in rice, but it is purposeful on broad impact QTLs/genes and ignores epistatic and genetic context effects. Most traits of interest to rice breeders are regulated by a combination of several small effect and/or major genes rather than a few large-effect genes. The use of genomic selection (GS) as an alternative to traditional MAS has been proposed. By the benefits per selection per unit time, GS has a huge potential to improve breeding efficiency. GS breeding enables breeders to use genome-wide DNA marker data to choose the most suitable parents for the next generation. The association between genome-wide markers and phenotypes of the individuals under selection is used to choose these parents. The major benefits of GS over MAS is that genotyping is not limited to a subset of markers that target genes with significant effects, but instead uses all available marker data to predict breeding value. This aids in the prevention of data loss. Genes with a minor effect can be tracked and chosen based on all of the markers results. As the cost of genotyping decreases, GS will become more efficient method for improving rice breeding performance [48, 49].

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