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Impact of breeder seed multiplication and certified quality seed distribution on rice production in India

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Abstract

Background: The All India Coordinated Rice Improvement Project (AICRIP) organizes multi-location tests (METs) with new genotypes from breeding programs. The best performing genotypes in METs for 3–4 years are identified and notified as commercial cultivars by the Government of India (GOI) to authorize breeder seed (BS) production.

Methods: We created a database and analyzed data on BS production for 24 years (1995–96 to 2018–19) in 475 inbred and 22 F_1 hybrid cultivars. Estimates were made to rank cultivars on the proportional contribution of a cultivar, quantity produced and a new BS index. Correlation and regression analyses were used to find the relationships between BS, certified quality seed distributed (CQSD), and milled rice production. We compared cultivars in BS production chain with those grown in farmers' fields across the country as identified in the production-oriented surveys.

Results: The top ten inbred cultivars identified are Jaya (notified by GOI in 1969), Swarna, Kranthi, IR 36, Sarjoo 52, Samba Mahsuri and Pusa Basmati 1 (notified in 1980–1989), and IR 64, Vijetha and Cottondora Sannalu (notified in 1991–2000). BS production in hybrid F_1 was insignificant. We detected a Pearson correlation ($r = 0.806$, $P < 0.01$) between the BS production and CQSD, and a linear relationship between the annual rice production in India and the CQSD ($R^2 = 0.850$, $P < 0.01$). The rice area coverage in 2018–19 with CQSD estimated was 41%. A total of 1877 cultivars (528 notified and 1349 not notified) were found at farms in rice growing districts in India.

Conclusions: From 1995–2019, BS and CQSD together increased the annual milled rice production in step with increases in population. Diverse rice genotypes have enabled rice to endure crop constraints in fragmented landholdings spread over 43 m ha. AICRIP's efforts have sustained availability of > 73 kg rice per capita per year (~ 40% of food grains). The process of notification, receipt of indent for BS from states, allotment and BS production, and de-notification of a cultivar by GOI need a review to ensure profits to farmers. As the 1000-seed weight varies in cultivars, it must be notified by GOI to adjust seed rate and maintain the recommended plant population at the farms. There is scope to increase the priceless BS production in cultivars to raise the country's production further, facilitate export and ensure profits to all stakeholders.

Keywords: Rice, Breeder seeds, Certified quality seeds distribution, Stability of production, Landrace, Inbred varieties, Hybrid varieties, Age of variety

Background

New rice genotypes are generated continuously with an improvement in one or the other traits of economic importance from the breeding activity at the national agricultural research institutes (NARI), state agricultural universities (SAU) and private seed industries. The

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first and the largest national multi-environment testing (MET) program was initiated by ICAR (Indian Council of Agricultural Research) in 1965 under the All India Coordinated Rice Improvement Project (AICRIP), now known as the ICAR-Indian Institute of Rice Research (IIRR) (ICAR-IIRR 1966). Similar experiments were initiated globally in 1975 by the International Rice Research Institute (IRRI) (IRRI 1975, 1980; Seshu 1992). An inter-disciplinary and inter-institutional collaboration is promoted in breeding line or genotype testing and development through the AICRIPs network of experimental stations throughout the country (Shastry 1993). All genotypes are put into initial evaluation or variety trial (IET or IVT) by assigning a neutral number and are grouped, depending on the maturity duration and grain type, into different trials (Shastry 1993; ICAR 1992; Paroda 1992; Paroda and Siddiq 1993). In the first year of MET, genotypes are simultaneously tested in screening nurseries to assess their reactions to biotic and abiotic stress. The best performing genotypes for yield and other traits of value are promoted to advanced evaluation or varietal trial (AET1 or AVT1); then on their performance in AET1 in the second year, some are further selected and promoted to AET 2 (or AVT2), in the third year. These genotypes in AET1 and/or AET2 are also subjected to agronomical trials and grain quality analysis besides screening for biotic and abiotic stresses (Paroda 1992).

The technical program for the conduct of trials is followed uniformly at all coordinating units. The cost of funding cooperating scientists and other expenses are shared by ICAR's AICRIP and SAU or voluntary center (at 75:25%). Monitoring tours are organized for promoting mutual trust on the conduct and performance of trials by involving participating scientists from SAU, NARI, and developmental staff in rice-growing districts. Seed technology centers are included in the distinctness, uniformity and stability (DUS) test (Prasad et al. 2020). During the crop season every year, multi-disciplinary teams of participating scientists conduct production-oriented surveys (POS) at random in many rice-growing districts of the country to document cultivars and identify constraints in farms (ICAR-IIRR 1995). Annual three-day rice workshops are organized by AICRIP at different locations of SAU or NARI, inviting all the associated scientists using funds granted by ICAR. The technical staff from the Departments of Agriculture in states, the center, national and state seed organizations, and private industry engaged in rice development, and a few farmers are invited to the workshops. Leading rice scientists from the IRRI participate on invite and interact extensively with all participants. The results from METs, screening nurseries and POS reports are analyzed every year at the workshop by cooperating scientists and members of variety identification committee of ICAR. Mini-kit, operational research farm and frontline demonstrations (ICAR-IIRR 1966; Shastry 1993) provide valuable information on how a pre-release cultivar performs in farmers' fields and its acceptance. After exhaustive deliberations, the best genotypes are identified for release. Besides settling on a technical program, the production and protection technology recommendations identified as useful for the ensuing production season are presented and thoroughly discussed, on the final day. Later, members of central sub-committee on crop standards, notification & release of cultivars (CSCSNRC) of Government of India (GOI) further scrutinize the data on proposed cultivars for release (ICAR 1992). On confirmation of the value of a newly proposed cultivar to farm production at two or more states, the CSCSNRC releases it by giving essential data for commercial cultivation, and the GOI issues gazette notifications authorizing BS production. Requisitions or indents for breeder seed (BS) are placed by Departments of Agriculture of various states, and seed producers from across the country with the Directorate of Seeds, Ministry of Agriculture, GOI. After critical review, BS production targets in cultivars are allotted by GOI through AICRIP to respective originating breeders. Some of the newly developed genotypes are also released for commercial cultivation to farmers within a state by the respective state cultivar release committee (SCRC). GOI issues notification for such newly proposed inbred or F_1 hybrid cultivars by SCRC only if they have undergone METs of AICRIP. BS of notified F_1 hybrid cultivars is directly distributed to farmers. Using the BS of notified inbred cultivars, certified quality seeds are produced by either public or private seed organizations and distributed to farmers in the country (GOI 1996). Seed standards for foundation or certified seeds are of 98% purity, 2% (max) inert matter, 10/kg (max) other crop seeds, 2% (max) objectionable weed seeds, 80% (min) germination, 13% moisture in ordinary container and 8% (max) in vapor proof container, and < 0.05% other distinguishable cultivars (ICAR 1992; Sastry et al. 2004; GOI 1988, 2013). For certified seeds, relaxation is provided for objectionable weed seeds (maximum of 5%) (GOI 2021b). The National Seeds Corporation (NSC) and the State Farms Corporation of India (SFCI) undertake seed production programs for a new inbred cultivar, using the BS supplied by the breeder in two stages as foundation seed I and II, which are respectively, multiplied as certified seed stages I and II (ICAR 1992; Rai 1992). BS of inbred cultivars multiplied at university farms are also supplied to state seed farms operated by NSC and the State Seeds Corporations (SSC).

A few attempts have been made to discuss the organization and seed production in India (ICAR 1992; Sastry et al. 2004; Muralidharan et al. 1996a; Muralidharan and Siddiq 1997; GOI 2002; ICAR-AICARP 2018). Witcombe et al. (1998) attempted to relate seven year data from six states on BS indents and CQSD by GOI with the spread or age of a rice cultivar. Singh et al. (2017, 2020) studied breeder seed indents in the context of notified commercial cultivar adoption by farmers and seed replacement rate. There is no information on the contribution of released cultivars to BS produced each year and to rice production in the country. Between 1969 and 2020, 1017 inbred and 106 hybrid rice cultivars were released by CSCSNRC and SCRC, and notified by GOI for commercial cultivation (ICAR-IIRR 1966; GOI 1996). These cultivars were released based on the data generated from experiments performed under AICRIP at 117 locations in 26 states of India in rainfed upland, hills (upland and irrigated), rainfed shallow lowland, semi-deep water (< 50 cm), deep water (> 50 cm water depth in field) and irrigated ecosystems; and aerobic (dry), boro (using residual moisture after kharif), and scented (Basmati and other aromatic) rice groups (ICAR-IIRR 1966). We critically examined the contribution of the commercial inbred and F1 hybrid rice cultivars in BS production chain, and compared them with those grown by farmers in different districts from 1995–96 to 2018–19. We further analyzed the data on BS production along with the annual data on cultivated area, production and certified seed distribution in India (GOI 1996) to assess the extent of involvement of notified cultivars and their contributions to rice production in the country.

Methods

Breeders seed production

The methods of Harrington (1952) and Shastry (1993) were followed to produce BS in inbred cultivars. The CMS plants were hybridized by pollinating with pollens from restorer plants to produce BS in commercial F_1 hybrid as per the well-established methods (Yuan and Virmani 1988; Virmani et al. 1998; Virakthamath et al. 2012). Seeds from single plant progeny rows of a cultivar were used to raise seedlings in a separate weed-free nursery plot for 15–21 days. In a weed-free field, seedlings of the cultivar were planted at a spacing of 5 cm between individual plants and 50 cm between lines (5 × 50 cm). A basal dose of green manure at 1.0 t ha^{-1} was applied before ploughing the field and fertilizers were applied at a uniform rate (120 kg N:60 kg P_2O_5:40 kg K_2O ha^{-1}). The entire dose of phosphatic and potassic fertilizers together with one-half of the nitrogenous fertilizer were also applied as a basal dose in the last plough. The remaining nitrogenous fertilizer was applied in equal doses at tillering and booting stages of crop growth. Appropriate recommended plant protection measures were used to control weeds, diseases and insects (ICAR-IIRR 1966). The breeder seed plot was examined until crop maturity for differences from the standard sample of the cultivar. Any suspected rogues and off-types were removed by cutting after taking precaution to prevent any contamination in the field. The grain type and size, and days to flowering and maturity were recorded in the cultivar. After approval by the monitoring team of AICRIP, BS was harvested, threshed, cleaned by post-harvest processing, dried (~ 12% moisture) and packed in new gunny bags (capacity 30 kg). These bags were tagged with golden yellow label giving all details, stitched, sealed and supplied for further production of foundation and certified quality seeds in stages (ICAR 1992; Sastry et al. 2004). We created a database on the actual BS production of 475 notified and 20 not notified inbreds, and 22 F_1 hybrids notified by GOI as cultivars for commercial cultivation in India from 1995 to 2018 (Additional file 1: Table S1, sheet 1). In India, the annual rice production data for the kharif and the ensuing rabi seasons are recorded and presented together (ICAR-IIRR 1966; GOI 1996). For example, the 1995–96 data represents the kharif (wet, June–November) 1995 and the following rabi (dry, Dec–March) 1996 seasons. The area cultivated to rice (million ha), CQSD of cultivars (expressed as quintal (100 kg) in India), and rice production (as milled grains), from 1995–96 to 2018–19 were gathered (Additional file 1: Table S1, sheet 2). This data set also included details on inbred and F_1 hybrid cultivars notified for commercial use by GOI (Additional file 1: Table S1, sheet 3), and the breeding centers where they were developed (Additional file 1: Table S1, sheet 4). Data were analyzed with MS Excel 2013 and SAS version 6.

Proportional contribution of an inbred cultivar

The proportional contribution of a cultivar in any year is influenced by other cultivars in the BS production system. The contribution of a cultivar to the BS production over 24 years (1995–96 to 2018–19) was estimated as a weighted proportion, in two steps: the BS produced in a cultivar was weighted as its proportion to the total BS produced in all cultivars in that year accounted for by that cultivar. Thus, the weight (*Wi*) is the amount of BS produced for a cultivar in a year divided by the total weight of BS produced in all the cultivars in that year. The total of these weighted proportions of BS produced in a cultivar over years was derived and the relative contribution of that cultivar to the BS production was assessed, from 1995–96 to 2018–19.

If, Y_{ij} is the quantity of BS produced in *ith* cultivar in the *jth* year,

w_{ij} is the weight of contribution of *ith* cultivar to BS production in the *jth* year,

BS_{ij} is the net quantity BS in *ith* cultivar in n_j year,

n_j are years—1, 2,.....*j* (1995–96, 1996–97 .....2018–19, in this study), and W_{ij} is the total proportional contribution of *ith* cultivar across years BS produced, then,

$$w_{ij} = Y_{ij}/BS_i \quad \text{(Eq. 1)}$$

Total proportion of *ith* cultivar across years,

$$W_{ij} = \sum_{J=1}^{nj} w_{ij} \quad \text{(Eq. 2)}$$

BS Index of an inbred cultivar

To find the value of individual inbred cultivar in the BS production system over years without any influence of other cultivars, a new BS index for each cultivar is calculated by giving weight for the number of years it was produced as follows:

$$\text{BS index} = \sum_{j=1}^{nj} jBS_{ij} / \sum_{j=1}^{nj} j \quad \text{(Eq. 3)}$$

where *j* is the natural number 1, 2, 3, up to n_j years, and n_j is the number of years BS produced in *ith* cultivar.

Relationships between area, production and CQSD of cultivars

In the annual data on the rice area (GOI 1996), production and CQSD from 1995–96 to 2018–19 (Additional file 1: Table S1, Sheet 2), the area cultivated and the milled grain production at farms across India are exposed to varying climatic conditions from year to year that exert some influence. To use available data set on area under rice cultivation and performance of grain production, it is crucial to remove the extraneous data or < noise > observed, if any, over the yearly variations. The methodology of Brisson et al. (2010) was used to choose a reference year and then to correct the yields step by step, based on the values over two consecutive years in the data set.

If, Y_{mjc} be the corrected value of the *jth* year; $\overline{Y}$ be the grand mean; and Y_{mjc} also be the corrected mean value of $Y_{mj.}$, then,

$$Y_{mjc} = (Y_{m1} + \overline{Y})/2 \quad (1)$$

and

$$Y_{mc} = \sum_{j=2}^{n} \frac{[Y_{mj} + Y_{m(j-1)}]}{2} \quad (2)$$

where *Y* represented the area or the production value.

Thus "year effect" was calculated relative to the year $j+1$, using the previously calculated "year effect" corrected to area or production value, and so on for all the years posterior to *j*, and identically for all the years anterior to *j* (using $j-1$). In the data set, the year variable for rice area or production (Additional file 1: Table S1, Sheet 2) was corrected with the calculated respective grand mean, $\overline{Y}_{area}$, for the area or $\overline{Y}_{prod}$, for production.

Pearson correlation was measured on the degree of association between the annual quantity of BS produced and the quantity of CQSD (Gomez and Gomez 1984). The linear regressions were performed to estimate the relationships between the milled rice production and the area cultivated to rice, BS quantity produced or certified quality seed distributed (CQSD) over the years. Residual plots were evaluated for occurrence of visual pattern and coefficients of determination were calculated. The criteria used to identify the best-fit models were the significance of model parameters (Student's *t*-test), coefficients of determination (R^2 and $R_a{}^2$ that adjusts for the number of explanatory terms in the model relative to the number of data points), and the lowest root means square of standard error (RMSE), while meeting the assumptions of normality, independence and homogenous variance in regression analysis (Rao 1965; Neter et al. 1985; SAS Institute 1988).

Rice area coverage by CQSD of cultivars

The extent of annual coverage of rice cropped by CQSD was estimated using the annual statistics on rice area and CQSD in the country (GOI 1996). A variable seed rate for inbred cultivar has been recommended over the years: 30 kg ha^{-1} for transplanted (Rai 1992), 100 kg ha^{-1} for direct seeded and 35–40 kg ha^{-1} for transplanted in 2010, 75–100 kg ha^{-1} for direct seeded, and 50–75 kg ha^{-1} for transplanted in 2012, and 25–40 kg ha^{-1} for transplanted rice in 2020 (GOI 1996, 2020). AICRIP recommended a generalized seed rate of 100 kg ha^{-1} for direct seeded and 40 kg ha^{-1} for inbred cultivar, and 15 kg ha^{-1} for F_1 hybrid for transplanted crop (ICAR-IIRR 1966). Therefore, rice area coverage of CQSD was derived by dividing the quantity of CQSD by the AICRIP-recommended seed rate ha^{-1} for inbred or F_1 hybrid cultivars.

Rice cultivars grown in farmers' fields

Data was assembled on rice genotypes grown by farmers across the country as sampled by the POS for 24 years (ICAR-IIRR 1995). The cultivars found in the survey were compared with the cultivars used in the production of BS.

Results

BS Production in inbred cultivars

Breeder seed (BS) production (Additional file 1: Table S1, sheet 1) was limited to 475 inbred and 22 F_1 hybrid cultivars notified by the GOI, from 1995–96 to 2018–19, (Additional file 1: Table S1, sheet 3) that included IR8 and Jaya released for commercial cultivation in 1969. The number of inbred cultivars released in BS production chain varied: 22 from 1970–1979, 76 from 1980–1989, 83 from 1990–1999, 175 from 2000–2009, and 117 inbred cultivars from 2010–2018. The BS production was in 54 cultivars (1184 q) in 1995–96; it steadily increased to 212 cultivars (5235 q) in 2010–11 and to 218 in 2018–19 (Fig. 1). However, the annual quantity of BS production reached the highest quantity of 11,404 quintals in 2012–2013.

The BS production chain was dominated by inbred cultivars released for irrigated and rainfed ecosystems (73% of all cultivars). The BS production (1995–2018) in notified inbred cultivars in different groups also varied: 197 cultivars in irrigated early, mid-early and medium; 152 cultivars in rainfed shallow and upland groups; 73 in scented group and irrigated rice-saline/alkaline; 12–18 in irrigated hill and semideep water; and 2–6 in aerobic, boro rice, deep water, hill upland, and irrigated-late groups (Table 1).The coefficients of variation of BS production in 4–6 inbred cultivars were high (22–44%) in hill irrigated, hill upland and irrigated-late groups. The CVs were low (10–18%) in BS production with many other notified cultivars. The BS production from 1995–2018 was 28,220 q in 63 inbred cultivars released for irrigated early group. It varied from 11,931 to 20,209 q, in cultivars released for irrigated mid-early (58) and irrigated medium (76), and rainfed shallow lowland (86 cultivars) ecosystems. The BS production varied from 6555 to 92,289 q in cultivars commercialized in rainfed uplands (66) and scented rice group (52 cultivars).

Most of the inbred cultivars were with long slender (186 cultivars, 39%) and medium slender grains (126 cultivars, 27%) in BS production from 1995–2018; other most preferred cultivars were with long bold (Ramaiah 1985) and short bold grains (66–86 cultivars, 14–18%). Only 11 cultivars with short slender grain were in the BS multiplication system (Table 2). Inbred cultivars commercialized were in 14 different categories, to cater to the demands of rice growers in India (ICAR-IIRR 1966). In terms of days taken to reach 50% flowering (DF), they were in five distinct groups (Fig. 2).

The BS production in inbred cultivars varied from one to twenty-four years for the period of 1995–96 to 2018–19 (Tables 3 and 4). BS was produced in 101 cultivars for only any one year and in 50 others for two years. These inbred cultivars accounted for a paltry share of 0.6–0.7% in the total BS produced in 24 years with 475 inbred cultivars. BS was produced in 17–32 cultivars for 4–11 years and in 2–11 cultivars for 12–24 years. The quantity of BS also varied with the numbers of cultivars used in the BS multiplication system. Interestingly, more BS was produced in two cultivars (Cottondora Sannalu and Krishna

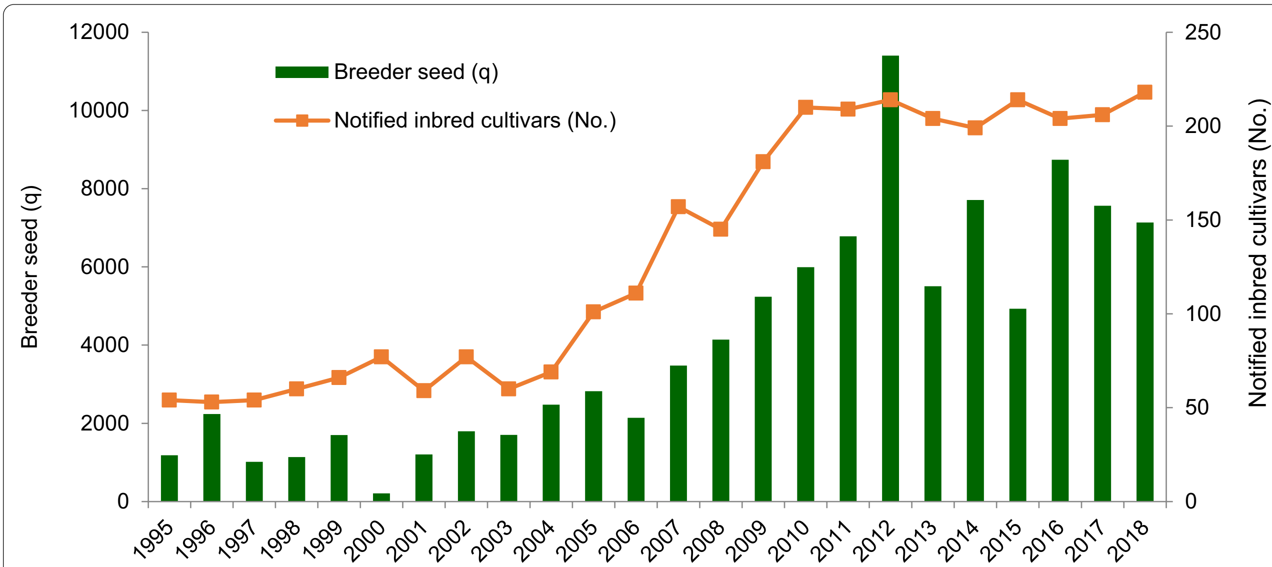

Fig. 1 Breeder seed produced for 24 years in commercial inbred rice cultivars notified by the Government of India from 1995–96 to 2018–19. Source data: Additional file 1: Table S1

Table 1 BS production in different rice ecosystems/ groups of inbred cultivars notified by the Government of India from 1995–96 to 2018–19

No.	Ecosystem /group	Cultivar (No.)	BS production (q)				CV (%)
			Total	Min.	Max.	Mean	
1	Aerobic rice	6	245.00	1.00	139.80	40.83	17.66
2	Boro rice	6	323.78	3.37	154.81	53.96	14.36
3	Deep water rice	2	142.80	37.50	105.30	71.40	9.70
4	Hill rice irrigated	18	568.35	0.41	190.50	31.58	22.21
5	Hill upland rice	5	63.54	0.10	54.31	12.71	38.14
6	Irrigated-early	63	28,220.36	0.10	12,276.15	447.94	9.34
7	Irrigated-late	4	24.70	0.10	15.90	6.18	43.80
8	Irrigated medium	76	19,128.22	0.10	2823.30	251.69	8.73
9	Irrigated mid-early	58	11,930.83	0.30	5216.26	205.70	12.86
10	Irrigated rice-saline/alkaline	21	1050.65	0.10	245.85	50.03	16.73
11	Rainfed shallow lowland	86	20,209.43	0.60	4899.48	234.99	11.23
12	Rainfed upland	66	9228.46	0.24	1591.10	139.83	11.77
13	Scented rice	52	6555.04	1.00	1001.68	126.06	11.73
14	Semi deep water	12	556.04	1.00	238.91	46.34	17.52
	Grand total	475	98,247.19	0.10	12,276.15	206.84	13.53

Source data: Additional file 1: Table S1

Table 2 Grain type (Ramaiah 1985) of 475 inbred rice cultivars notified by Government of India from 1995–96 to 2018–19 in BS production chain

Groups	Long slender (LS, KL > 6 mm, and L/B > 3.0)*	Medium slender (MS, KL < 6 mm, and L/B of 2.5–3.0)	Short slender (SS, KL < 6 mm, and L/B of > 3.0)	Long bold (LB, KL > 6 mm, and L/B of < 3.0)	Short bold (SB, KL < 6 mm, and L/B of < 2.5)	Cultivars (No.)
Aerobic rice	3	2		1		6
Aromatic short grains		2			3	5
Basmati group	4					4
Boro rice	2	3			1	6
Deep water rice		1			1	2
Hill rice irrigated	5	1	1	3	8	18
Hill upland rice		2		1	2	5
Irrigated-early	27	15		12	9	63
Irrigated-late		2			2	4
Irrigated medium	33	26	1	14	2	76
Irrigated mid-early	25	15	4	9	5	58
Irrigated rice-saline/ alkaline	8	3		6	4	21
Rainfed shallow lowland	18	35	2	15	16	86
Rainfed upland	24	11	1	22	8	66
Scented rice	35	5	2		1	43
Semi deep water	2	3		3	4	12
Grand total	186	126	11	86	66	475

Source data: Additional file 1: Table S1, *Kernel length (KL)

Hamsa) for 19 years (6552 q, 7% share), and in three cultivars (Annada, Kranthi and Pant Dhan 12) for 20 years ((13,086 q, 13% share) during the period from 1995–96 to 2018–19. Many old inbred cultivars were in BS production system for more than 20 years. BS was produced for a period of 24 years in several old cultivars IR 36 (1982),

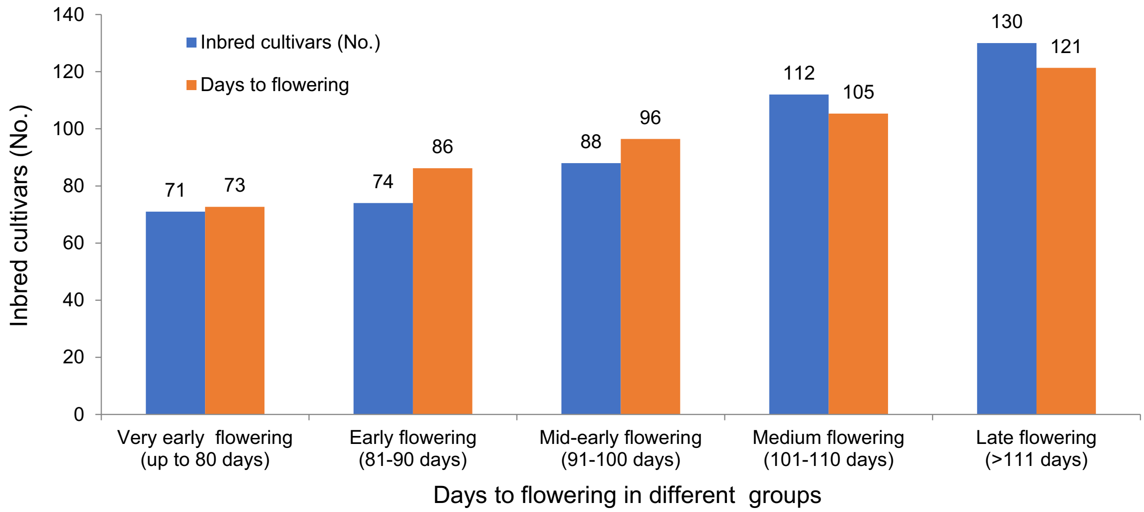

Fig. 2 Frequency distribution of days to flowering in 475 inbred cultivars notified for commercial cultivation by the Government of India from 1998 to 2018. Source data: Additional file 1: Table S1, sheet 3

IR 64 (1991), Jaya (1969), Mahsuri (1974), Pant Dhan 10 (1993), Pusa Basmati 1 (1989), Rasi (1978) and Samba Mahsuri (1989) (Table 4).

Additionally for 12 years, a total of 100 q of BS was produced in 20 inbred cultivars that were not notified for commercial production by GOI (Additional file 2: Table S2 sheet 1). BS production with two inbreds was 14 q in 1998 and was 18 q with six other inbreds in 2016 and 2018. The highest quantity of BS produced was in the inbred cultivar, Red Triveni (13 q) in 1998.

Contributors to breeding and development of cultivars

Inbred and F_1 hybrid cultivars notified from 1995–96 to 2019–20 for commercial cultivation were developed at 77 different breeding centers (Additional file 2: Table S2 sheet 2). Several inbred genotypes developed outside India were received under the exchange program. These exogenous genotypes were also evaluated and a few identified as useful in METs of AICRIP were released and notified by GOI: 18 cultivars from IRRI, Philippines; four from Bangladesh Institute of Nuclear Agriculture; three from Sri Lanka; and one each from China, Indonesia and Malaysia. The contributions towards cultivar notification for release were from NRRI (58), from Bhubaneswar (36), from IIRR and Raipur (23 each), 10–18 from seven centers, 2–9 from 40 centers, and one cultivar from each of the other 25 AICRIP centers.

Ranking inbred cultivars by contribution to BS production and BS index

The contribution of a cultivar to BS production over 24 years (1995–2018) estimated as a weighted proportion was high in cultivars Kranthi (1.93) and IR64 (1.62), Swarna (1.36), Cottondora Sannalu (1.14), IR36 (1.03) and Samba Mahsuri (0.94) (Additional file 2: Table S2 sheet 3). The magnitude of BS produced, the number of years multiplied, the BS index and proportional contribution to total BS in each notified cultivar from 1995–96 to 2018–19 were used to rank and select the top ten cultivars (Table 5). Seven of these top-ranking cultivars were released for cultivation in only one state; three cultivars, IR 64, IR 36 and Pusa Basmati 1 were released for cultivation in 3–4 states. All these 10 cultivars have been in BS production for 19–24 years. Cultivars released for irrigated ecosystems dominated BS production with three each for early (80–90 days) and medium (101–110 days), in addition to one cultivar for irrigated mid-early (91–100 days) ecosystem. Other dominating cultivars in BS identified were Swarna and Samba Mahsuri (late > 111 days) for rainfed shallow lowland, and Pusa Basmati 1 for the scented group.

BS production in notified F_1 hybrid cultivars

BS production was limited to 436 q in 22 F_1 hybrids developed at AICRIP centers and notified by GOI (Table 6). BS production was in only three hybrids in 1998, increased to 7–10 hybrids from 2007 to 2015, and then reduced to four hybrids in 2018 (Additional file 1: Table S1). Nineteen notified F_1 hybrids for commercial production possessed long slender grains, two others had medium slender grains and one had long bold grains. The quantity of BS produced fluctuated from year to year; it varied from 0.18 q in 2000 with three F_1 hybrids, to 120

Table 3 BS production in cultivars for a specific period (No. of years), inbred cultivars used (No.), total BS produced (q), and share of a cultivar within the multiplication period to total BS (%)

BS production in cultivars (period)	Cultivars used for BS Production (No.)	BS production (q) Total	Minimum	Maximum	Mean	CV (%)*	Share of a cultivar to total BS (%)*
1-year only	101	632	0.10	124.97	6.26	61.49	0.64
2-years	50	667	0.41	100.00	13.35	33.58	0.68
3-years	48	1707	0.70	385.55	35.55	22.56	1.74
4-years	21	1027	3.21	213.44	48.89	14.51	1.05
5-years	23	1930	0.87	334.70	83.93	12.31	1.96
6-years	29	1419	6.00	245.18	48.92	14.52	1.44
7-years	32	2204	4.79	304.70	68.87	12.23	2.24
8-years	17	3095	10.50	1591.10	182.07	10.59	3.15
9-years	29	6945	5.00	2297.80	239.49	8.73	7.07
10-years	26	7832	18.30	1279.82	301.23	6.04	7.97
11-years	19	3621	9.70	1103.01	190.57	8.31	3.69
12-years	6	1753	63.00	681.00	292.19	5.16	1.78
13-years	11	2417	33.22	908.50	219.75	7.49	2.46
14-years	8	1646	68.34	477.75	205.72	6.09	1.68
15-years	5	2007	175.27	780.00	401.41	3.89	2.04
16-years	6	2240	147.62	1024.70	373.30	4.83	2.28
17-years	10	3644	107.50	1141.40	364.38	4.84	3.71
18-years	6	1504	117.11	470.31	250.61	4.87	1.53
19-years	2	6552	154.81	6397.34	3276.08	2.03	6.67
20-years	3	13,086	254.30	12,276.15	4362.09	1.90	13.32
21-years	6	5924	93.75	2823.30	987.28	3.23	6.03
22-years	5	3234	157.55	1118.03	646.85	2.95	3.29
23-years	4	7837	352.99	4899.48	1959.16	2.34	7.98
24-years	8	15,325	357.49	5216.26	1915.67	2.18	15.60
Grand total/mean	475	98,247	0.10	12,276.15	206.84	13.53	100

Share of each cultivars to total BS produced within the specified period in inbred cultivars notified by GOI from 1995–96 to 2018–19

*Coefficient of variation (CV%)

Source data: Additional file 1: Table S1

q in 2009 with eight hybrids, and then reduced to 2 q in 2018 with four hybrids.

Progress in milled grain production and CQSD

From 1995–96 to 2018–2019, the area cultivated to rice remained nearly stable at 43.6 ± 1.2 m ha (STD, 1.07, CV, 2.45%); the milled rice production gradually increased from 72 to 116 m ha (STD, 11.77, CV, 12.44%) (Additional file 1: Table S1 sheet 2, Fig. 3).

The CQSD also increased from 15 to 74 m t but the quantity varied from year to year (STD, 24.07, CV, 50.45%) (Additional file 1: Table S1 sheet 2, Fig. 4). When estimated at the recommended seed rate of 40 kg ha^{-1}, certified quality seed distributed annually covered increasingly more area, since 1995. The coverage of cultivated rice area with CQSD was 4 m ha in 1995–96 and increased to cover 21 m ha of sown area in 2016–17. However, CQSD area coverage decreased to 18 m ha in 2017–18. The meager quantities of F_1 hybrid cultivar seeds (Table 6) are directly sown without any further multiplication as foundation and certified seeds. Therefore, the area coverage of cultivated hybrid rice in 1998 was extremely limited to 26 ha, increased to 802 ha in 2009, and drastically reduced to 3 ha in 2018.

Relationships between rice production, area cultivated, and CQSD

Considering the time lapse between BS and CQSD for 2–3 years, Pearson correlation coefficients estimated were $r = 0.806$ (n = 18, $P < 0.01$) and $r = 0.799$ (n = 17, $P < 0.01$) for two- and three-year time lapses, respectively. This indicated a very good association explaining more than 80% relationship between the BS produced and the CQSD distributed in each year. The linear regression

Table 4 Breeder seed (BS) production for a specific period (No. of years) in inbred rice cultivars

BS production in cultivars (period)	Name of inbred rice cultivars
1-year only	ADT 32, ADT 42, ADT 49, Aiswarya, Ajit, ASD 18, Bhagheerathi, Bhalum 2, Bhavapuri Sannalu, Binadhan 10, Binadhan 12, Binadhan 8, Birsa gora 102, Birsa Vikas Dhan 111, Birsa Vikas Dhan 203, Birsadhan 103, Chandra, China 988, CN 1272-55-105, CO 43, CO 43 Sub 1, CR Dhan 101 (Ankit), CR Dhan 310, CR Dhan 800 (Swarna-MAS), CR Sugandh Dhan 907, CR Sugandh Dhan 910, Dandi, Dhala Heera, DRR Dhan 47, GAR 13, Gautam, Gitesh, GR 104, GR 8, GR 9, Hari, Harsha, IR 8, Jagityal Samba, JR 767, Kalachampa, Kalanamak 3, Kanchana, Karimnagar Samba, KHP 9, Kohsaar, Kunaram Sannalu, Lakhimi, Madhuri, Mahanandi, Malviya Sugandha Dhan, MO 5, Narendra Dhan 80, Narendra Jal Pushp, Narendra Mayank, Nidhi, Palam Dhan 957, Palghar 1, Pant Dhan 24, Pathara, Pinakini, PMK3,Prasanna, Pratheeksha, Priya (CR Dhan 209), Punjab Basmati 4, Punjab Basmati 5, Pusa 1612, Pusa 169, Pusa Basmati 1609, Pusa Basmati 1637, Pusa Basmati 1728, Radhi, Ramappa, Ratnagiri 2, Ratnagiri 5, Samalei, Sampriti, Shanthi, Sharavathi, Shyamala, SKL 8, Sonamani, Sonasali, Sree Kurma, Sri Druthi, Sugandha Samba, Surya, Swarna Shreya, Swathi, Taramati, Tarangini, Tarunbhog Selection 1, TKM 9, TRY 1, Udayagiri, Usar 1, Vallabh Basmati 24, VL dhan 206, VL Dhan 207 and Vyttila 6
2-years	ADT(R) 47, Anashwara, ASD 19, Ashwini, Badshahbhog Selection 1, Bhadrakali, Birsa Vikas Dhan 108, Chhattisgarh Zinc Rice 1, CR 1009 Sub 1, CR Dhan 201, CR Dhan 300, CR Dhan 303, CR Dhan 304, CR Dhan 305, Dhiren, DRR Dhan 44, DRR Dhan 45, Dubraj Selection 1, GIZA 14, Gontra Bindhan 3, HKR 48, Indira Sugandhitdhan 1, Jagabandhu, Kanchan, Kesava, KHP 5, Kotha Molagolukulu 74, Mugad Siri 1253, Mugad Sugandha, Onam, Pant Sugand Dhan 17, PKV Ganesh, PKV Khamang, PNR 546, PR 103, PR 126, Pratibha, Ratnagiri 4, Saket 4, Sarathi, Shravani, Sindewahi 75, SJR 5, Triguna, Vagaddhan, Vajram, Varun Dhan, Vishnubhog Selection 1, VL Dhan 157 and VL Dhan 68
3-years	Abhaya, Amulya, ASD 16, Barah Avarodhi, Bathukamma, Bhuban, Binadhan 11, Chinsurah Rice, CO 51, CR Dhan 307 (Madhumani), CR Dhan 40, CR Dhan 501, CR Dhan 601, CSR 43, DRR Dhan 42(IR 64 Drt 1), DRR Dhan 43, DRR Dhan 46, Durga, Early Samba, Indira Aerobic 1, Jagjivan, Karjat 8, Malviya Dhan 36, Mukthi, Narendra Dhan 118, Narendra Usar 2, Neela, Parbhani Avishkar, Phule Radha, PKV Makarand, PNR 519, Prakash, Pratap, Punjab Basmati 3, Pusa 1592, Pushpa, Ranbir Basmati, Sachala (CR Dhan 203), Samba Mahsuri Sub 1, Satya, Shalimar Rice 1, Sujala, Tawi, Telangana Sona, Turant Dhan, Type 3, Varsha and VL Dhan 86
4-years	ADT(R) 46, Chandan, Chandan (CR Boro Dhan 2), Chandrama, CSR 10, Daya, Haryana Basmati 1, HKR 120, Jaldidhan 6, Matta Triveni, Narendra Usar Dhan 2008, PNR 162, PR 121, PR 122, PR 123, PR 124, Sugandha, Sugandhamati, Vallabh Basmati 22, Vikas and Virender
5-years	Aditya, Barani Deep, Bhrigu Dhan, CSR 23, Deepti, IGKVR 1, IGKVR 2, Indira Barani Dhan 1, Jagityal Mahsuri, Jajati, Jhelum, Karjat 6, Kharveli, Maheshwari, Mahi Sugandha, Manohar Sali, Narendra Lalmati, NDR 2065, PR 108, Punjab Basmati 2, Pusa Basmati 1509, RP 2421 and Sashi
6-years	ADT 38, CR Dhan 500, CSR 13, GR 7, IR 30,864, Jal Lahari, Jaldidhan 13, Jogesh, Karjat 184, Lachit, Malviya Dhan 1, Moti, Narendra Dhan 3112–1 Prakhar, Nua Chinikamini, Padmini, Pankaj, Pant Dhan 18, Phalguni, Prabhat, Pusa 677, Reeta (CR Dhan 401), Sidhanta, Tapaswani, Tejaswani, Vanaprabha, Varadhan, Vasundhara, Vivek Dhan 62 and VL Dhan 65
7-years	Athira, Bharani, BR 2655-9-3-1, Chenab, CR Dhan 10, CR Sugandh Dhan 3, Gajapathi, GR 4, Hanseswari (CR Dhan 70), Hazaridhan, HKR 126, Karjat 2, Konark, Luna Sampad, Luna Suvarna, Malviya Sugandh 105, Malviya Sugandh 4-3, Mandakini, Mandya Vijaya, Mrunalini, NDR 2064, Nellore Mahsuri, Pant Dhan 16, Pant Dhan 6, Pant Sugand Dhan 15, Ratnagiri 1, Ratnagiri 24, Sujatha, Upahar, Vivek Dhan 154, VL Dhan 208 and VL Dhan 209
8-years	Amara, Basmati 386, Chaitanya, Heera, Indrayani, Jaldubi, Kalinga III, Karjat 5, Luit, Narendra Usar 3, Nua Kalajeera, Pardhiva, Phule Samrudhi, Sadabahar, Sahbhagi Dhan, Shusk Samrat and Tunga
9-years	Abhilash, Abhishek, ADT(R) 48, Akshayadhan, CSR 27, Gurjari, HKR 127, Indra, Kanak, Karjat 3, Karjat 7, Karma Mahsuri, Ketakijoha, Malviya Dhan 2, Manaswini, Pusa Basmati 6, Rajendra Bhagwati, Rajendra Kasturi, Rajendra Suwasini, Ramachandi, Rani Dhan, Rashmi, Richa, Srikakulam Sannalu, Swarna Sub 1, Vasumati, VL Dhan 221, VL Dhan 85 and Warangal Sannalu
10-years	Bahadur, Birsa Vikas Dhan 110, Birsamati, Gontra Bidhan 1, GR 11, HPR 1068, HPR 2143, IET 7191, Improved Samba Mahsuri, Krishnaveni, Maruteru Sannalu, Narendra 8002, Naveen, Pant Dhan 4, PKV HMT, Pusa 834, Pushyami, Rajendra Mahsuri 1, Rajendra Sweta, Samleshwari, Sampada, Surendra, Swarnamukhi, Thanu, Utkal Prabha and Varshadhan
11-years	ADT 36, ADT 44, Bamleshwari, Bhadra, Bhogavati, Birsa Vikas Dhan 109, Chandrahasini, Dhanrasi, Dharitri, Erra Mallelu, Gayatri, Jarava, Naina, Pant Dhan 19, Polasaprabha Mahsuri, Pratikshya, Sukardhan 1, Surekha and Tulasi
12-years	Geetanjali, Improved Pusa Basmati 1, Khandagiri, PAU 201, Pusa Sugandh 5 and Warangal Samba
13-years	HKR 47, Kasturi, Kavya, PR 115, Pusa Sugandh 4, Sabita, Sarala, Sita, Somasila, Tholakari and Vandana
14-years	ADT(R) 45, Anjali, Danteshwari, Godavari, Parijat, Phalguna, PR 118 and Pusa Sugandh 3
15-years	Basmati CSR 30, Poornima, Pusa Sugandh 2, Shatabdi and Uma
16-years	ADT 43, Jagityal Sannalu, PNR 381, Pooja, PR 106 and Swarnadhan
17-years	ADT 37, ADT 39, CR 1014, IR 20, Khitish, Mahamaya, PR 114, PR 116, Rajshree and Ranjeet
18-years	Basmati 370, IR 50, Pant Dhan 11, PR 113, RatnaandTaraori Basmati
19-years	Cottondora Sannalu and Krishna Hamsa
20-years	Annada, Kranthi and Pant Dhan 12
21-years	Jyothi, Lunishree, Narendra Dhan 97, Narendradhan 359, Sona Mahsuri and Vijetha
22-years	Govind, Intan, Lalat, Pusa 44-33 and Tella Hamsa
23-years	PR 111, Sarjoo 52, Savitri and Swarna
24-years	IR 36, IR 64, Jaya, Mahsuri, Pant Dhan 10, Pusa Basmati 1, Rasi and Samba Mahsuri

Commercial inbred cultivars (total 475) notified by GOI from 1995–96 to 2018–19

Source data: Additional file 1: Table S1

Table 5 Top 10 notified inbred rice cultivars by BS produced years, proportional contribution, BS quantity and, BS index (1995–96 to 2018–19)

Rank	Cultivar*	Notified*	Ecosystem/ group**	Age (on 2019)	States (No.)	BS Years	Proportional contribution	Quantity BS (total q)	BS index
1	Kranthi	1982	IRE	37	1	20	1.93	12,276	953
2	Cottondora Sannalu	2000	IRE	19	1	19	1.11	6397	439
3	IR 64	1991	IRME	28	1	24	1.62	5216	257
4	Swarna	1980	RSL	39	1	23	1.36	4899	270
5	IR 36	1982	IRE	37	3	24	1.03	2826	118
6	Samba Mahsuri	1989	RSL	30	1	24	0.94	3524	187
7	Jaya	1969	IRM	50	20	24	0.54	1123	39
8	Vijetha	1997	IRM	22	1	21	0.69	2823	166
9	Sarjoo 52	1982	IRM	37	1	23	0.66	2016	94
10	Pusa Basmati1	1989	SCR	30	4	24	0.42	1002	40

Source data: Additional file 1: Table S1

*Notified by for commercial production by GOI, **IRE = irrigated early, IRME = irrigated mid-early, IRM = irrigated medium, RSL = rainfed shallow lowland and SCR = scented rice

Table 6 Breeder seed (BS) production in notified commercial F_1 hybrid cultivars (1998–99 to 2018–19)

No.	Ecosystem/ group	F_1 Hybrid cultivar	DF	GT	Notified (GOI)	Developed at	States (No.)	BS (q)	Years BS produced
1	IRME	Ajay	98	LS	2006	NRRI	1	2.95	3
2	IRME	APHR 1	95	LS	1997	Maruteru	1	3.21	3
3	IRME	APHR 2	95	LS	1997	Maruteru	1	2.00	1
4	IRM	DRRH 1	101	LS	1998	IIRR	1	2.28	4
5	IRE	DRRH 2	86	LS	2005	IIRR	4	5.85	7
6	IRM	DRRH 3	103	MS	2010	IIRR	5	1.10	5
7	IRM	Haryana Shankar Dhan 1	104	LS	2007	Kaul	1	2.95	2
8	IRME	Indira Sona	98	LS	2007	Raipur	1	3.00	3
9	IRE	JRH 5	87	LB	2007	Jabalpur	1	0.50	1
10	IRE	JRH 8	90	LS	2009	Jabalpur	1	1.00	2
11	IRME	KRH 1	95	LS	1996	Mandya	1	2.70	3
12	IRM	KRH 2	105	LS	1998	Mandya	15	231.44	15
13	IRME	KRH 4	97	MS	2015	Mandya	2	1.80	2
14	IRM	Pant Sankar Dhan 1	105	LS	1999	Pantnagar	1	15.50	7
15	IRME	Pant Sankar Dhan 3	92	LS	2006	Pantnagar	1	10.75	6
16	SCR	Pusa RH 10	85	LS	2001	IARI	4	111.80	10
17	Boro	Rajalaxmi	128	LS	2006	NRRI	2	3.05	3
18	IRME	Sahyadri 1	100	LS	2000	Karjat	1	22.59	12
19	IRE	Sahyadri 2	85	LS	2007	Karjat	1	3.86	11
20	IRME	Sahyadri 3	95	LS	2007	Karjat	1	4.41	12
21	IRE	Sahyadri 4	88	LS	2009	Karjat	5	1.30	4
22	RSL	Sahyadri 5	113	LS	2016	Karjat	1	2.18	2
Grand total (BS q)								436.22	

Boro Boro rice, *IRE* irrigated-early, *IRME* irrigated mid-early, *IRM* irrigated medium, *RSL* rainfed shallow lowland, *SCR* scented rice, *DF* days to flowering, *GT* grain type, *LS* long slender (kernel length > 6 mm, and L/B of > 3.0); medium slender (MS, kernel length < 6 mm, and L/B of 2.5–3.0)

Source data: Additional file 1: Table S1

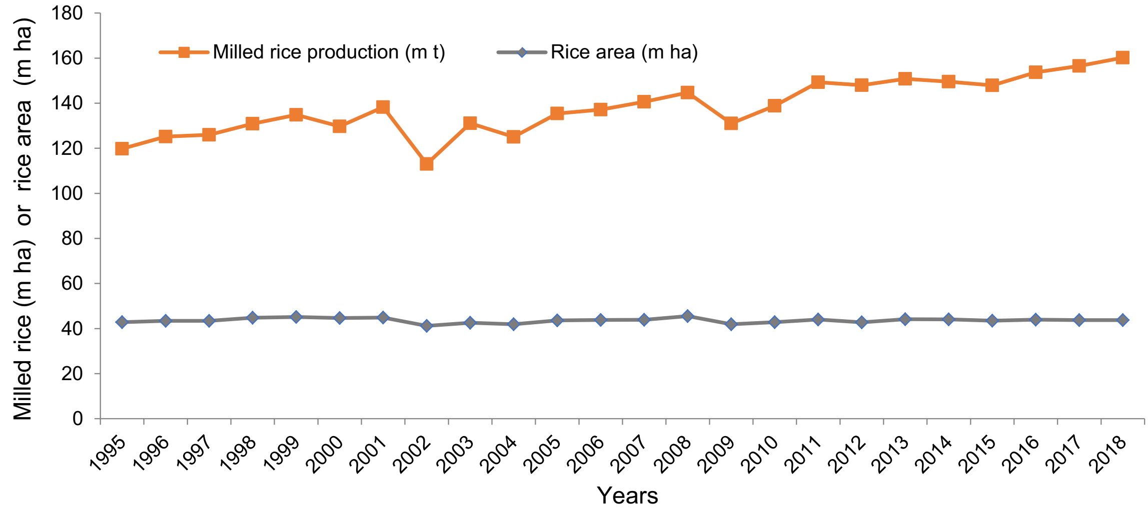

Fig. 3 Trend in the area (m ha) and milled rice production (m t) from 1995 to 2018 in India

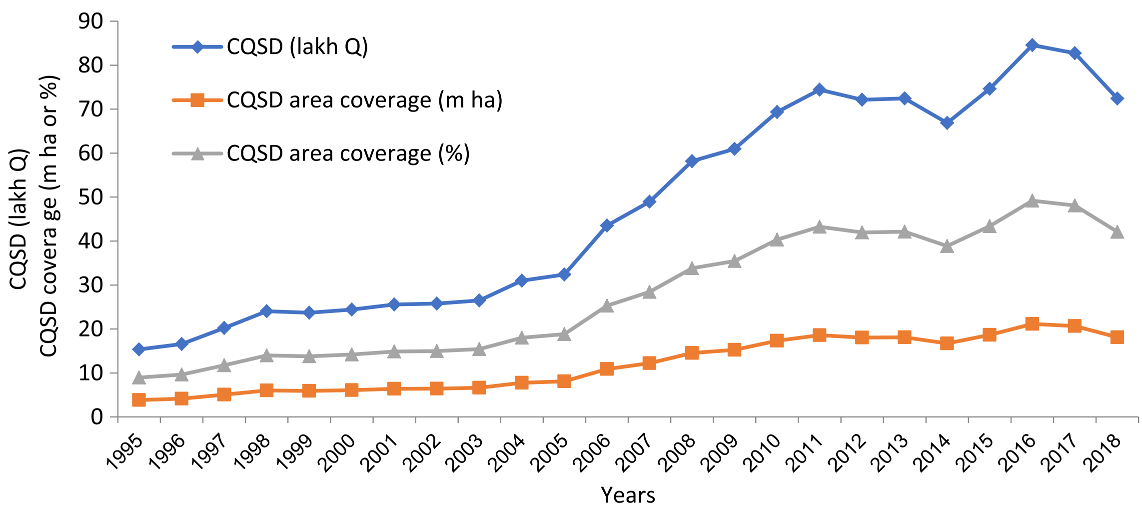

Fig. 4 Trend in the certified quality seed distributed (CQSD lakh q) in notified cultivars and coverage of rice area under cultivation (m ha and in percentage) by CQSD from 1995 to 2018 in India. Source data: Additional file 1: Table S1, *lakh q = 0.1 million kg

Table 7 The linear regression models describing the relationships between rice production (Y) and area (X_1) or certified seed distribution CQSD (X_2) or area (X_1) and CQSD (X_2)

$Y = 24.546^{NS} + 1.602X_1^{NS}$, $R^2 = 0.011^{NS}$, RMSE = 9.799 … Eq. 4
$Y = 76.751^{**} + 0.370X_2^{**}$, $R^2 = 0.856^{**}$, $R_a^2 = 0.849^{**}$, RMSE = 3.741 …Eq. 5
$Y = 9.648^{NS} + 1.538X_1^{NS} + 0.370X_2^{**}$, $R^2 = 0.866^{**}$, $R_a^2 = 0.853^{**}$, RMSE = 3.693 … Eq. 6

Source data: (Additional file 1: Table S1 sheet 2); lakh q = 0.1 million kg

n = 24 years (1995–96 to 2018–2019), Y = milled rice production (m t), X_1 = area (m ha), X_2 = certified quality seeds distribution (CQSD lakh quintals*) models showed non-significant relationship between area and grain production (Table 7, Eq. 4). The relationship was highly significant between the quantity of CQSD and rice production over the years (Eq. 5). This positive effect on production exerted by the quantity of CQSD was further confirmed in the model developed by regressing area and CQSD together on rice production (Eq. 6). There was no significant relationship between production and area (Eq. 4). The intercepts (coefficients for rice area, $X1$) were non-significant in Eq. 4 and Eq. 6. The intercept (coefficient for CQSD) was highly significant ($P<0.01$) in Eq. 5. In contrast, the coefficients for X_2 (CQSD) were same and highly significant ($P<0.01$). R_a^2 was about the same for the models with only X_2 (CQSD), and for both X_1 (area) and X_2 (CQSD) (0.849 and 0.853, respectively). Therefore, the linear model developed by regressing production on CQSD (Eq. 5) is more valid. The scattered points around the prediction line found in residual plots further confirmed the appropriateness of this model.

Rice genotypes in farmers' fields

Many rice genotypes were found under cultivation in farmers' fields in the production-oriented surveys across rice-growing areas in India (ICAR-IIRR 1995). In each of 26 states of India, annually 2–14 districts have been surveyed (Fig. 5) and the genotypes grown by farmers in their fields were listed (Additional file 2: Table S2 sheets 4 and 5). Starting with 56 districts in 1995, the number of districts surveyed annually increased to more than 100 from 1999 (Fig. 6). The number of genotypes listed varied with the states: they were 5–9 in Andaman & Nicobar, Arunachal Pradesh and Rajasthan; 22–35 in Kerala, Manipur and Tripura; 52–79 in Punjab, Puducherry and Telangana; 93–98 in Assam and Jammu & Kashmir; and over 100 in other states. The farmers in the country cultivated many genotypes, aromatic, Basmati, F_1 hybrid, local, private and cultivars between 1995 and 2018. During the last 24 years, in surveys in farmers' fields, 1877 genotypes (Figs. 7 and 8) were recorded, which included 528 notified and 1349 not notified cultivars (Additional file 2: Table S2 sheets 4 and 5). Strangely, farmers preferentially grew more genotypes that were not-notified by GOI than the notified cultivars. Local cultivars not notified by GOI dominated with 918 genotypes, 49% of all records enumerated at farms in 24 years of POS. Similarly, not notified aromatic and private inbred and F_1 hybrid cultivars were also found more in numbers in farms than notified cultivars.

Discussion

Seed generation, distribution and rice production in India

India produced 122.7 m t of milled grains from rice grown in 45.0 m ha in 2020–2021 (GOI 2021). The recommended seed rate was 30 kg/ha for sowing rice. The seed requirement was estimated at 9.2 m t (ICAR-IISS

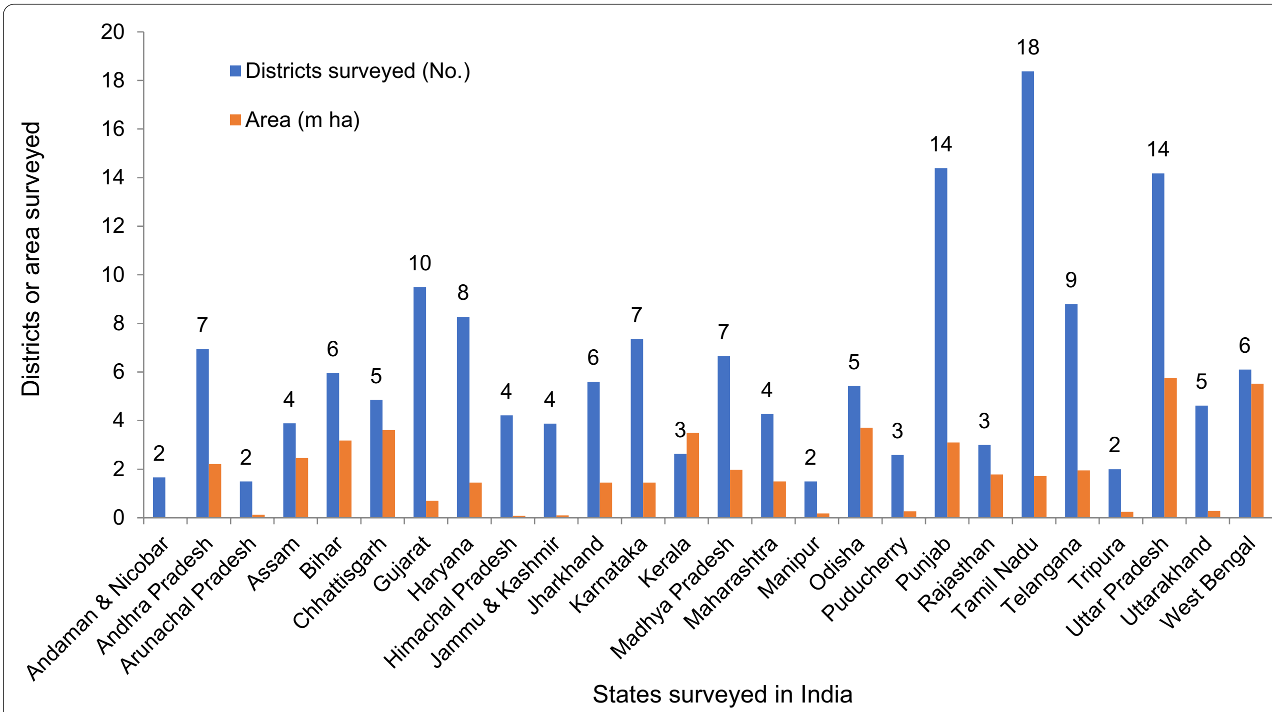

Fig. 5 Production oriented survey in rice growing districts of 26 states in India from 1995–2018 (ICAR-IIRR 1995)

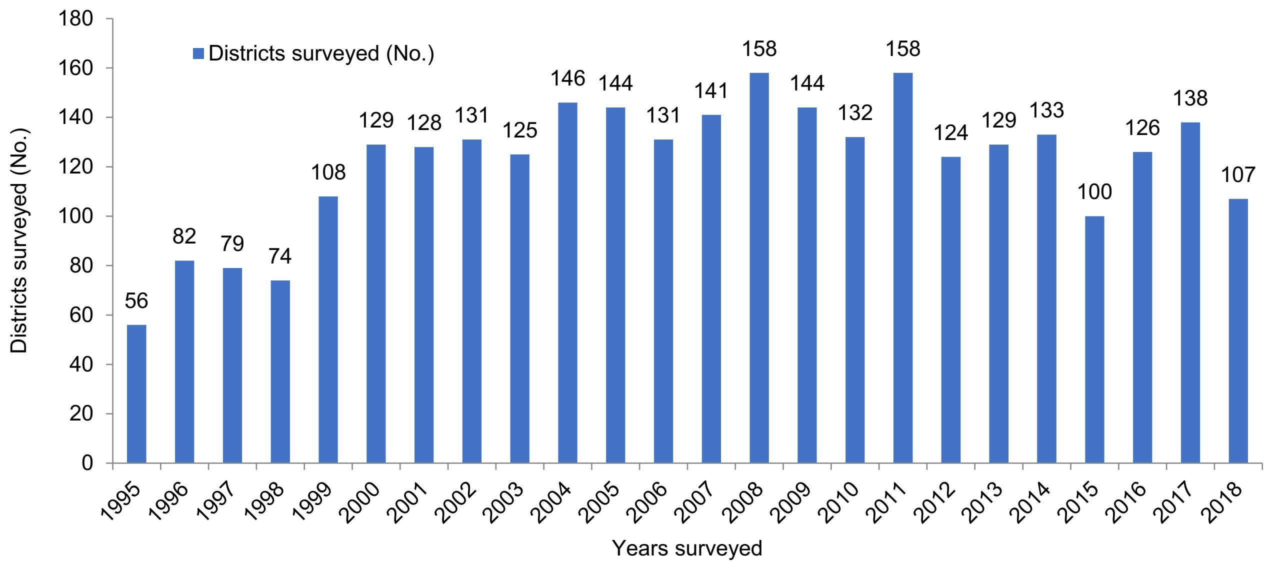

Fig. 6 Annual production oriented survey in rice growing districts in India from 1995–2018 (ICAR-IIRR 1995)

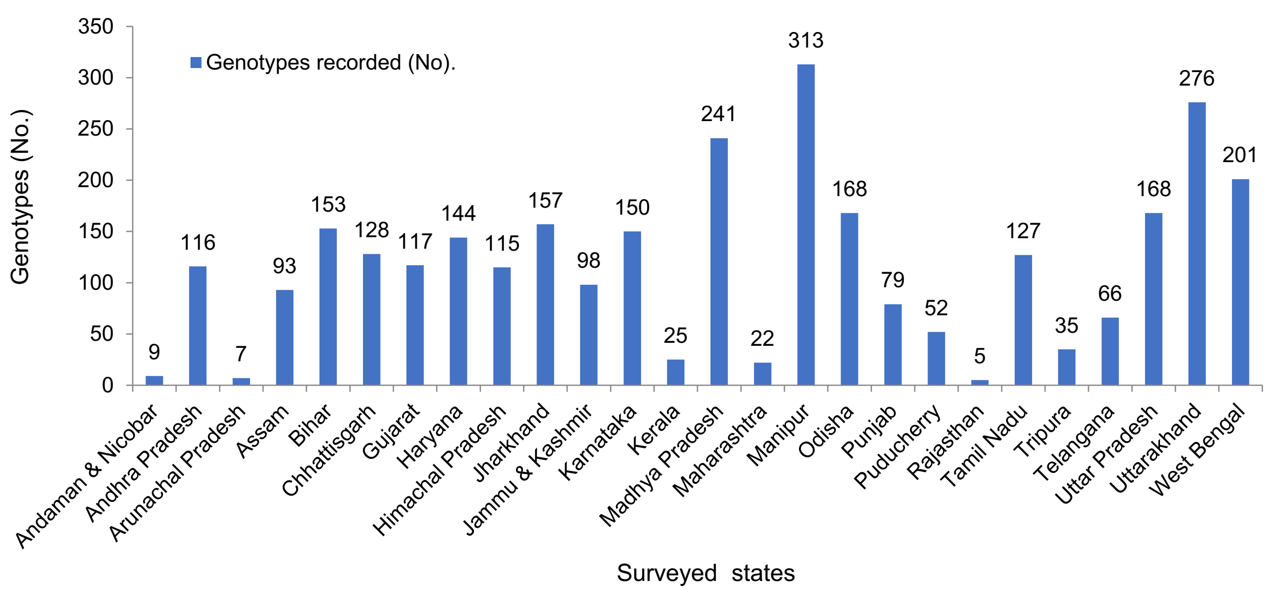

Fig. 7 Total number of rice genotypes recorded in production oriented surveys in different states in India from 1995 to 2018 (ICAR-IIRR 1995)

2021). The breeder seed indent is applied based on state government target which is derived on the randomly fixed seed multiplication rate (~80-times) (Rai 1992) and seed replacement rate (40%) (ICAR-AICARP 2018). The total breeder seed produced was 1912 t in rice varieties notified by GOI. The certified quality seed distribution to rice farmers was 8.463 m t. About 4.0 m t of certified or truthfully labeled rice seeds were made available to farmers by private seed firms (GOI 2021).

Uncertainty in notification or de-notification of cultivars and BS production

From 1969 to 2020, a total of 1123 (1017 inbred and 106 F_1 hybrid) cultivars were notified for commercialization (ICAR-IIRR 1966; GOI 1996). The production of BS is permitted in these notified cultivars by GOI, only for a period of fifteen years from the date of their release, as per the Seed Rules 196 of the Seed Act 1966 and PPV&FR Act 2001, Bill No. 123-C of 1999 (GOI 1966, 2001). While

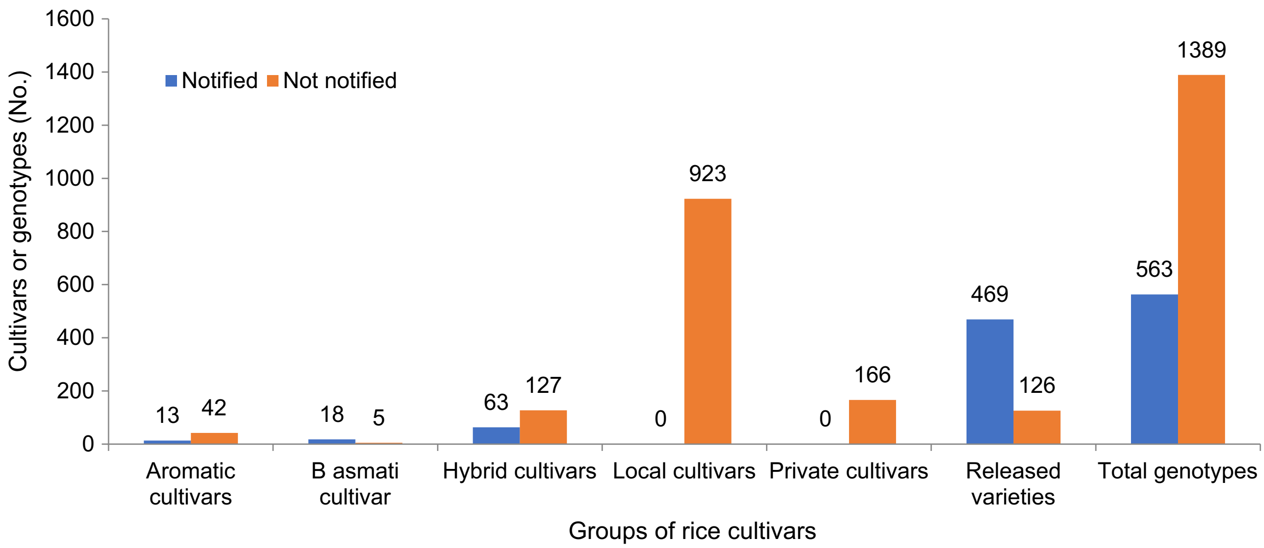

Fig. 8 Notified and non-notified rice cultivars and genotypes recorded in production oriented surveys in different states in India from 1995 to 2018 (ICAR-IIRR 1995). Source data: Additional file 2: Table S2 sheets 4 and 5

the BS production from 1995–96 to 2018–19 was substantial over years in 475 inbred cultivars (96,036 q), it was extremely low and limited to only 22 F_1 hybrids (436 q) developed by AICRIP centers. Several concerns may contribute to risk-averse innovation strategies among private seed companies (Rutsaert et al. 2021). The F_1 hybrids developed by private firms have benefitted from the AICRP's METs for the evaluation and identification for release and notification by GOI for commercial use. Financial assistance is also provided by the Government of India (GOI 2020) for the training, production and distribution of F_1 hybrid seeds to public organizations and private seed business firms. Yet, public records are not available on the demands raised by the extension departments or GOI to produce BS seeds in 84 privately owned F_1 hybrids. Reliable data on seed sales and uptake by cultivar type in developing regions remain very scarce (Donovan et al. 2021). It is important to review and correct this skewed public–private partnership to foster harmonious relations and data sharing between the two partners.

BS was produced in 20 other cultivars that were identified by AICRIP, but not notified by GOI for commercial production, apparently in anticipation of a notification by GOI. By 1987, 56 inbred cultivars were de-notified by GOI as they were considered as no longer needed to produce rice in farms. Strangely, despite de-notification, BS production continued in several of these de-notified cultivars. For example, BS was produced in IR 8 in 2000 in spite of its de-notification in 1976 by GOI (Additional file 1: Table S1). Panels of experts examine the indents received from different states at the Directorate of Seeds, GOI and at the National Seeds Project of ICAR. Later they decide to allot the quantity of BS production in notified cultivars. On receipt of the allotment letter from GOI, BS is produced (ICAR 1992). Besides the delay in notification process for several years (3–4) in some cultivars, a further delay is caused due to non-receipt of allotment of GOI for BS production on-time after their notification for commercialization (Rai 1992; Singh et al. 2020; Virk 1998; Prasad et al. 2017). BS produced at high cost in several new cultivars identified by AICRIP, but not notified by GOI are wasted as it cannot be further multiplied or distributed. It is evident that AICRIP's efforts, time and money spent on identifying new, genetically improved genotypes through painstaking METs are not utilized if they are not notified to aid their commercial use. Of the 672 inbred cultivars notified from 1995–2018, BS production was limited to 475 inbred cultivars (inclusive of those cultivars notified from 1966). Details on BS produced in many cultivars authorized by SCRC are not available in the public domain due to the absence of a timely communication. The existing communication system between the concerned breeders, state and central agencies involved in BS production is, apparently, the stumbling block in following these instructions contained in the PPV&FR Act (GOI 2001). This process must be hastened to make BS production more effective. In this age of fast digitalization and high speed internet, facilities are already well-established for use at all these organizations. Therefore, an urgent review is required on the process of notification, receipt of indent for BS from states, allotment, BS production and de-notification by GOI to ensure profits to farmers from the phenomenal cooperative efforts of METs of AICRIP.

Survival of inbred cultivars and their contribution

Witcombe et al. (1998) estimated the age of an inbred cultivar using limited seven-year data on BS indents and CQSD in six states of GOI by adopting the index of Byerlee and Heisey (1990) that was developed for understanding the proportion of area covered by a cultivar. They concluded that the age of rice cultivars to indents do not represent actual BS production. Our estimate using actual data over 24 years on BS production (not on indents) indicated that the age of an inbred cultivar cannot be generalized. While 199 released and notified inbred cultivars were multiplied in BS production chain for 1–3 years, 273 cultivars were multiplied 4–24 years (Tables 3, 4). BS is further multiplied in stages as foundation and certified quality seeds for 2–3 years, and distributed to farmers. Evidently, many of the cultivars identified by AICRIP and notified by GOI continue to survive in fields beyond two to five decades after release (Table 4, Additional file 1: Table S1, Additional file 2: Table S2). The cultivar Kranthi notified in 1982 for cultivation exclusively in the eastern parts of Madhya Pradesh has dominated BS production in terms of quantity for 19 years till 2018–19. BS production is continued in IR8 and Jaya (1969) and Mahsuri (1974), Rasi (1978), IR 36 (1982), Samba Mahsuri (1989), Pusa Basmati 1 (1989), IR 64 (1991) and Pant Dhan 10 (notified for release in 1993). The estimates on the quantity of BS produced in each notified inbred cultivar, new BS index and proportional contribution to total BS production over years were used to rank the dominant cultivars in the BS chain from 1995–96 to 2018–19 (Table 5). The top ten inbred cultivars in BS production identified were Kranthi, IR 36, Cottondora Sannalu, Jaya, Sarjoo 52, Vijetha, IR 64, Swarna, Samba Mahsuri and Pusa Basmati 1, released from 1982 to 2000. These inbred cultivars have further confirmed their durability and endurance in farms across India and continued to enhance the rice production (Muralidharan et al. 1996a, 2019). AICRIPs team efforts in METs and arriving at a consensus in selection and identification of new genotypes for cultivar release by GOI, after an exhaustive debate at each workshop, have ensured their ageless longevity, yield stability and preference by farmers. This is in contrast to hybrid rice cultivars with marked reduction both in numbers and quantity of BS. The low quantity of F_1 hybrid seed production of < 1.5 t ha^{-1} and obstacles in finding skilled labor on time prevent an exploitation of yield heterosis in hybrids (Virakthamath et al. 2012). The BS production in a cultivar in any year cannot be assumed to be influenced by other cultivars, especially when area under rice crop is exceptionally large (43 ± 1.2 m ha) in the country. BS in all inbred rice cultivars are used to produce CQSD. The importance of CQSD is evident from the positive and highly significant relationship detected between milled rice production and CQSD (Table 7). The age of a cultivar in a BS production chain can be estimated from the date of its release and notification by GOI. The age of a cultivar is not affected by the quantity produced or other cultivars in BS chain.

Considering farmers' preferences in BS seed production

Rice genotypes cultivated by farmers in different districts in various states in India have been recorded in the AICRIP's production oriented surveys made by several teams of scientists from coordinating centers and development staff from the state departments of agriculture (ICAR-IIRR 1966). Risk aversion, household size, family income, landholding area, risk-free off-farm job, credit availability, and easy access and cost of seeds influence farmers to cultivate landrace with farm-saved seeds (Bannor et al. 2020). Registration was completed in 1836 farmers' cultivars and local landraces till 2018 (GOI 2022). The first constraint in POS is that it does not necessarily proclaim to cover all the areas under rice. The second drawback is the lack of a proper plan to statistically cover all the rice-growing districts. Yet, the annual surveys have listed cultivation of nearly 1877 genotypes (528 notified and 1349 not notified) in farms in more than 100 rice-growing districts in 26 states from 1995 to 2019. Therefore, genotype records in POS show less than the actual figures and thus are underestimated. The actual numbers of genotypes in farmers' fields would be of a much higher magnitude than that listed in POSs. Many aromatic old germplasm selections, Basmati-types, F_1 hybrids, local genotypes and cultivars developed by private seed firms are cultivated in districts. Evidence from POS indicated that countless genotypes including a few registered by farmers under PPV&FR Act (GOI 2001) are grown widely (Additional file 2: Table S2 sheets 4 and 5). Farmers are unacquainted with the legislation of PPV&F Rights Act, 2001, or of the Geographical Indications of Goods (Registration and Protection) Act 1999 (Blakeney et al. 2020). Census of all individual geo-localized farmers' fields, landraces and villages may be collected using GPS device to create a geo-spatial database (Huat et al. 2019; Arouna and Aboudou 2020). Private seed firms often successfully submit required details on their newly developed and named genotypes to obtain certification from the state governments to sell the seeds directly to farmers. The breeder seed indent is applied based on government target (GOI 2021). A challenge facing international seed systems is the need to make demand-orientated delivery of seeds (Conny et al. 2021). There is no effort to establish the nature of demand for improved rice seeds or choice of varieties (Mesfin and Zemedu 2018). Farmers regularly interact with breeders at AICRIP, SAU and private research centers. Myriad new genotypes in advance stages of breeding, selection and identification are easily accessed by them. All these genotypes are not notified by GOI in the absence of MET data of AICRIP. Apparently, these genotypes have varied genetic makeup and possess traits that are not only of interest to farmers but have better commercial prospects and thereby longevity. More than 86% of all landholding farmers have an operational area of < 1.5 ha (GOI 2015b). The stability in rice production achieved is evidently due to the cultivation of so many preferred old or aged genotypes in addition to hundreds of commercially notified cultivars in fragmented landholdings in monsoon-dependent farmers' fields in India.

About 9000 years BP, the human population at the Lahuradewa archaeological site of the Indo-Gangetic plains used the lake margin to cultivate rice (Thakur et al. 2018). India is a home for over 20,000 traditional landraces and 15,000 Indian cultivars are given to IRRI's germplasm bank (IRRI 1991). Most of these local cultivars were marked by distinct functional traits that assured livelihoods stability of the population and better suitable mechanisms to various biotic and abiotic stresses (Prasad et al. 2020). Crop landraces in rye are a superior material compared to elite breeds in terms of the distribution of genetic diversity resulting from crop evolutionary processes (Hagenblad et al. 2016). Farmers still grow old landraces of wheat (*Triticum* spp), which are important for grain production in Tajikistan (Husenov et al. 2021). Taiwanese landraces of rice possess various and unique genetic backgrounds (Hour et al. 2020). Although improved US cultivars were introduced in northern South America in the 1940s, these have not displaced the traditional landraces, which are cherished for their taste and nutritious qualities and for their importance in Maroon spiritual life (Tinde et al. 2019). Continued cultivation of old landraces was shown to reflect on the socio-cultural preferences in China (Wang et al. 2018). Farmers continue to grow old varieties. Sarjoo 52 (notified 1982), Savithri (1983), Bindeshwari (1981), Radha-4 (1994), Sona Mahsuri (1982), Samba Mahsuri (1989) and Mahsuri (1974) in Terai region that lies south of the outer foothills of the Himalayas (Witcombe et al. 2017; Thapa et al. 2019; Begho 2021). Rice varietal age in South Asian countries was estimated at > 20 years (Velasco et al. 2013). Sona Mahsuri, Sarjoo 52, Samba Mahsuri and Radha-4 cover the four major rice producing districts in Nepal and risk attitude is the determinant of rice farmers' adoption decision (Begho 2021).

The registration process may therefore be useful to ensure that the use of traditional varieties is adequately documented (Lushington 2012). EU seed laws, and their Member State implementation, have traditionally favored uniform crop production of commercialized breeds over conservation varieties, which have been a contributing factor to crop genetic erosion (Batten et al. 2021). In the regulatory framework in India, certification and registration of seed is voluntary and small farmers continue to grow their farm saved seeds in tiny pieces of land. Breeding for climate change focuses on genes with large effects on heat and drought tolerance, but phenology and stress tolerance are highly polygenic (Atlin et al. 2017). The priorities in trait development often do not consider farmer (or other stakeholder) preferences and needs (McEwan et al. 2021). Most rice landraces cultivated for a long period of time by farmers in India have apparently adapted to changes in climate, and to varying abiotic and biotic constraints. The question arises as to why the farmers' preferred genotypes are not selected and quality seed multiplied to enable increased production and farmers' profits? It is vital to initiate a program to test these genotypes in METs of AICRIP to aid a GOI-notification and thus generate CQSD.

A case for increasing production of BS and CQSD and seed export

AICRIP's efforts from 1995 to 2020 have ensured a sustained annual availability of > 73 kg rice per capita (~ 40% of food grains availability) in step with increasing population from 982 million in 1996 to 1393 million in 2021, and rice export (40 m t in 2021) (GOI 1996). India's success in increased rice production is reflected by the breeder seed production and our estimated area coverage (41%) in excess of the target of GOI. One limitation imposed in estimating the area coverage by CQSD is the variable seed rate recommended for sowing over years. The actual area covered with CQSD may be much less as ageing of seeds, seed deterioration and damage from poor storage conditions at farms across the country cause considerable loss in the quantity of seeds before reaching fields. The correlation coefficient derived explained more than 80% for the relationship between the BS produced inbred cultivars and the CQSD in India. Further, the relationship between CQSD and milled rice production over the years estimated by linear regression was highly significant. There is an untapped potential to increase production and distribution of certified quality seeds to farmers that guarantees rice security and satisfy increasing demands. Oddly, reports of the national seed project and similar accounts lament the non-utilization of BS produced as per requisitions received from states (Prasad et al. 2017; ICAR-IISS 2012). A few states have enforced at least a partial advance fund collection (~25%) with BS indent to ensure its utilization. Seed is the most valuable precursor to increase the overall production and profits to farming communities. The seeds produced by private industries are fully utilized as they practice several innovative methods to entice farmers to use their seeds. Often, the problem in public centers is the transfer, frictions between breeders or non-availability of the concerned breeder, and the consequent lack of persistence in pushing further BS into CQSD. It is crucial to find ways to enforce the responsibility of BS production and its utilization of each notified cultivar on its originating center.

AICRIPs multi-disciplinary approach in METs has generated many improved cultivars to suit diverse ecologies. The Indian cultivars that produced stable high yields in the international tests (Prasad et al. 2001a; Muralidharan et al. 2002) or those which possessed resistance to stresses or good quality traits have found wide acceptance and claimed commercial release in several countries around the world (Prasad et al. 2001a). India can effortlessly continue to help other rice-growing countries to attain as well as sustain self-sufficiency in the future. We have shown that the present production of BS in rice is decreasing. The seed multiplication rate was arbitrarily decided in 1992 at 80-times (Rai 1992), when milled rice yield was 2–2.5 t ha^{-1}. Yield in harvested milled rice has increased to 5–5.5 t ha^{-1} following annual commercial release of new inbred cultivars and better agronomical management (Muralidharan et al. 1996a, 2019). It is rational for GOI to review and declare seed multiplication rate at ~160-times. India has a comfortable surplus in rice production with a buffer stock of 13.58 m t compared with the mandated requirement of two million tonnes of un-milled paddy (GOI 2015a, 2022). The genetically modified varieties are expected to be released in future for commercialization. The accurate monitoring and quantification of genetically modified varieties are key factors to implement labeling regulations. Developing certified reference material of DNA from seed powder (Yang et al. 2018) or the other source is needed to evaluate genetically modified variety with appropriate analytical method or equipment.

With surplus production, there exists a potential for India to increase revenues through rice seed export. Seed quality assurance in India is under the jurisdiction of the Seeds Act (GOI 1966), wherein a quality seed must satisfy the requirements of the Indian Minimum Seed Certification Standards (GOI 1988, 2013). This quality assurance system for seed export comes under the Organization for Economic Cooperation and Development (OECD) standards and International Seed Testing Association (ISTA) methodology of seed testing. India as a member follows their prescribed formal system to maintain cultivar identity, genetic purity and production of quality seed with optimal physical, physiological and sanitary quality (Trivedi and Gunasekaran 2013, 2015). The global standards are rigidly practiced for land requirement, field crop inspection, seed testing, and pre- and post- production control processes for rice seeds sale. Further, the PPV&FR Act 2001 enforces the rights of breeders and farmers in seed trading, and provides opportunities to derive more economic returns to all concerned (GOI 2001). Besides those notified by GOI, cultivars that are included in the national list after DUS tests or test on value for cultivation and use (VCU) in at least one country also qualify for certification (Prasad et al. 2017; 2020). Ten State Seed Certification Agencies of the country are designated authorities to carry out the cultivar certification of the OECD Seed Schemes (Trivedi and Gunasekaran 2015). In addition to seed production within the country, aided with the government support, seeds of inbred and F_1 hybrid cultivars can be multiplied abroad to enable a higher participation in international seed trade. Trait-specific SNP and fingerprint markers are used to validate phenotypic data of rice landraces and cultivars for fragrance, pericarp color, amylose content, starch pasting properties, gelatinization temperature, resistance to disease, plant pubescence, and plant height (McClung et al. 2020; Yuan et al. 2022). It is vital to select variety-specific SSR markers and sequence DNA of varieties considered for export to authenticate the varietal distinctiveness.

Seed rate required to sow rice in one hectare

The decisive factors for rice production are plant population, effective panicles per plant, grain number per panicle, and grain or seed weight. In rice, single grain weight is genetically constant, irrespective of growth environments (Yoshida 1981), unlike differences from that of other cereal crops (Makino et al 2020). Grain weight is mainly governed by genes and QTLs (Zhu et al. 2019; Akabane et al. 2021; Hao et al. 2021; Qiao et al. 2021), whereas grain filling rate is affected by external environmental conditions (Si et al. 2016; Das et al. 2018; Li et al. 2019). Grain or seed weight, is typically stable despite changes in environmental and nutrient conditions (Chen et al. 2021) and seed processing eliminates partially filled seeds. The quantity of CQSD is often related to area covered by rice in India by using the recommended seed rate per hectare. A seed rate of 30 kg ha^{-1} for rice was fixed in 1992 (ICAR 1992). In 1995, the Department of Agriculture, GOI advocated a seed rate of 75–100 kg ha^{-1} for direct sown rice and 50–75 kg ha^{-1} for transplanted rice. However, in 2020, GOI recommended a seed rate as 20–40 kg ha^{-1} for rice (GOI 1996). These apparent arbitrary farm advisories on seed rate for different years for the same crop are confusing and not science-based prescriptions. The question is how the seed rate for use should be derived? It is well-known that rice cultivars differ in seed weight that is often expressed as 1000-grain weight. The 1000-seed weight varies from < 13 to > 30 g in *indica* rice cultivars (Virmani et al. 1998; Virakthamath et al. 2012; Sudharshan 2011; Reddy 2012; Kumar et al. 2013; Chandrika et al. 2015; Bian et al. 2020; TNAU 2021) (Additional file 2: Table S2 sheet 6) and to 48 g in T930 (Mualidhran et al 1996b). In *japanic* cultivars also the 1000-grain weight varied from 22 g in Akita 39, to 30 g in Atika 63, and 48 g in Oochikara (Makino et al. 2020). Therefore, a constant seed rate in two cultivars with the 1000-seed weight of 15 g in one and 30 g in another cannot result in the same quantity of seedlings. Seed rate must necessarily be adjusted to ensure adequate maintenance of the recommended plant population for achieving potential yields.

Farm advisories of AICRIP (ICAR-IIRR 1966; Muralidharan et al. 1990) recommend plant populations of 4.44 lakh hills ha^{-1} (at a plant to plant spacing of 15 × 15 cm) for early, mid-early maturing cultivars, and 3.33 lakh hills ha^{-1} (at a plant to plant spacing of 15 × 20 cm) for medium and late maturing cultivars to maximally exploit the yield potential of a cultivar. The farm advisory also recommends a transplanting at 2–3 seedlings/hill in inbred and planting 1–2 seedlings/hill in F_1 hybrid cultivar (ICAR-IIRR 1966; Virakthamath et al. 2012). Therefore, seed rate is to be corrected for a cultivar based on its 1000-seed weight, purity and seed viability. For illustrative purpose, it is demonstrated by using 1000-seed weight of a cultivar at prescribed seed standards of GOI to estimate the required seed rate for inbred and F_1 hybrid cultivars (Additional file 2: Table S2 sheet 7). The trait of seed weight in rice cultivars is considered in selection by breeders as it is well-known to be highly stable but is summarily ignored in GOI notification. When identifying in METs of AICRIP and notifying a cultivar for commercial cultivation, this stable trait of 1000-seed weight has to be necessarily included to facilitate adjustments to seed rate before use in fields.

Rice is cultivated under four major groups, viz. irrigated (22 m ha), rainfed lowland (14 m ha), flood prone (3 m ha) and rainfed upland (6 m ha) ecosystems in India (Muralidharan and Siddiq 1997; Muralidharan et al. 1996a, 2019, 1990; Prasad et al. 2001a, 1995). Nearly 85% of rice is direct sown in Eastern India (Muralidharan et al. 1988). In semideep and deep water areas and rainfed uplands, rice is grown using 60–100 kg seeds ha^{-1} as direct seeded crop[99]. Farmers may, in these fields, adopt direct seeding either before the onset of monsoon rains or broadcast sow pre-germinated seeds (50–55 kg ha^{-1}) in puddled soil (Muralidharan et al. 1990; Prasad et al. 1995; Singh et al. 2008; ICAR 2020). The farm advisory of GOI based on AICRIP data recommends the use of 100 kg seed rate ha^{-1} for direct seeding in rice (ICAR-IIRR 1966; GOI 1996). It is an efficient, resources conserving, mechanized, climate smart and economically viable strategy (Sagare et al. 2020) and is effective in rainfed lowlands (Ohnoa et al. 2018). Farmers increasingly use farm machinery in field preparation to level land more effectively, and opt for direct seeded rice. The machine sowing method with printed seeds by pasting seeds to paper (Shan et al 2020) can be developed to reduce the seed rate, establish uniformly high plant stand and increase grain yields (Xing et al. 2020). The estimation of the extent of direct-seeded rice is difficult especially due to fragmented small and marginal land holdings in India. Evidence stresses the need to increase BS production and CQSD by several folds, if more area is brought under direct seeded rice using the advocated higher seed rate per ha for sowing. A wide range of technologies and practices are available to upgrade seed quality, and enhance seedling and plant growth. Methods may be standardized to assess seed quality by using of multispectral imaging and near-infrared spectroscopy (Taylor et al. 2021).

Conclusions

From 1969–2020, 1017 inbred and 106 F_1 hybrid cultivars were developed, evaluated in METs and identified for release as improved varieties by AICRIP. They were notified for commercialization by the Government of India (GOI) to authorize breeder seed (BS) production. In notified cultivars BS production was significantly correlated with that of certified quality seed distribution (CQSD). The linear relationship between annual milled rice production and CQSD in India was also highly significant. A few thousands of local cultivars, landraces and other rice genotypes apparently differing in genetic make-up are grown in ~ 43 m ha of fragmented landholdings. Cultivation of diverse rice genotypes enabled to endure crop constraints and increase production. Increased rice production is reflected by the BS production and CQSD coverage (41%) in excess of the target of GOI. The impact of quality seed production and distribution to farmers is the sustained annual availability of > 73 kg rice per capita (~ 40% of food grains availability) in step with increases in population and rice export (40 m t in 2021). The process of notification, receipt of indent for BS from states, allotment, BS production and de-notification by GOI are to be critically examined to ensure profits to farmers from the phenomenal cooperative efforts of AICRIP. An assessment of public–private partnership is desirable to foster harmonious relations and data sharing on seed production.

Communication between central and state governments and private industry must ensure speed and accuracy on planning seed production and its distribution. The arbitrary declaration on rice seed multiplication rate five decades ago by the government needs a revision from 80- to 160-times. The trait of 1000-seed weight varies in rice cultivars from < 13 to > 30 g. Yet, it is ignored and omitted in the notification on commercial release of a variety. It must be obligatorily declared at GOI notification of a commercial cultivar to adjust seed rate used to ensure recommended plant population in the field. Farm advisories on seed rates are to be redefined for sowing transplanted or direct seeded rice by considering seed weight. It is vital to generate systematic geo-spatial distribution data on the area cultivated with local landraces and other genotypes to register claims. Following tests by AICRIP, the central or state governments may selectively notify registered landraces or genotypes to generate breeder seeds and distribute certified quality seeds to farmers. There is scope to further increase the priceless BS production in cultivars to raise the country's production, and facilitate rice seed and grain export to ensure profits to all stakeholders.

Abbreviations

ICAR: Indian Council of Agricultural Research; GOI: Government of India; ICAR-IIRR: Indian Institute of Rice Research; AICRIP: All India Coordinated Rice Improvement Project; IRRI: International Rice Research Institute; MET: Multi-environment tests; BS: Breeder seed; CQSD: Certified quality seed distribution; POS: Production-oriented Surveys; NARI: National Agricultural Research Institutes; SAU: State Agricultural Universities; CSCSNRC: Central Sub-committee on Crop Standards Notification & Release of Cultivars; SVRC: State Cultivar Release Committee; NSC: National Seeds Corporation; PPV&FR: Protection of Plant Variety and Farmers' Rights.

Supplementary Information

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Additional file 1: Table S1. Sheet 1 BS production in notified rice cultivars in India from 1995–96 to 2018–19, Sheet 2 Rice area, production and certified quality seed distribution (CQSD) in India from 1995–2018, Sheet 3 Details on inbred and hybrid cultivars notified by Government of India from 1969 to 2018 (ICAR-IIRR 1966–2020; GOI, 1969–2019), Sheet 4 Particulars on centres of AICIRP network used to produce breeder seeds in inbred and F_1 hybrid cultivars from 1995–96 to 2018–19.

Additional file 2: Table S2. Sheet 1 BS production in inbred cultivars identified by AICRIP but not notified by GOI (1995–96 to 2018–19). Sheet 2 Contribution of inbred cultivars (suitable for different ecosystem/group) developed at AICRIP and international participating centre (1995–2018). Sheet 3 The proportional contribution of an inbred cultivar estimated relative to other cultivars in BS production system, BS quantity and BS index (1995–96 to 2018–19). Sheet 4 Cultivars (No.) listed in POS (production-oriented surveys) from 1995 to 2018 in different rice growing states in India. Sheet 5 Cultivars listed in production-oriented surveys in farmers' fields in India from 1995 to 2018. Sheet 6 Variability in one thousand seed weight (1000-seed wt. g) in inbred and F_1 hybrid cultivars. Sheet 7 Estimating seed rate per hectare for sowing based on seed weight of rice cultivar to ensure adequate plant population of plants as recommended by AICRIP and GOI.

Author contributions

GSVP: Participated in conceptualization, data curation, resources, validation and drafted the manuscript; CSR: performed methodology validation and formal analysis; SK: verified data, and visualization; KM: Participated in conceptualization, data curation, analysis, visualization and original draft writing – review & editing; and EAS: participated in guiding, supervision, review. All authors read and approved the final manuscript.

Competing interest

The authors declare that they have no competing interests.

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