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REVIEW ARTICLE

Unravelling the output and outcome of field crops breeding in India since the implementation of the Seeds Act, 1966

J. S. Chauhan[$], P. R. Choudhury, K. H. Singh[1] and Vishnu Kumar[2]

Abstract

Crop breeding in India has been in progress for over 100 years and a large number of varieties of cereals, pulses, oilseeds, fibres and sugarcane have been released prior to the adoption of the system of official release of varieties in October 1964. However, the Government of India has legislated the Seeds Act, 1966, to regulate the quality of seeds of the varieties, which came into force on October 1, 1969. The present paper discusses the historical aspects of the initiation of the varietal improvement programme in India, as well as the status of field crop varieties released and notified during 1969-2025 in pursuance of section 5 of the Seeds Act, 1966 and the induction of recently released varieties (2019-23) in the current seed production chain. A total of 7488 high yielding, climate resilient, diseases and pest resistant/tolerant varieties/hybrids of 96 crops comprising cereals (13), food legumes (18), oilseeds (15), fibres (7), sugarcane, sugar beet, tobacco, forages (27) and other potential crops (13) including 604 varieties developed by the private sector, have been released and notified till 2025 employing both conventional and molecular breeding. These include 122 varieties of seven field crops (rice, wheat, maize, pearl millet, chickpea, lentil, soybean and groundnut) developed through molecular breeding and 170 bio-fortified varieties of 16 field crops (rice, wheat, maize, barley, pearl millet, finger millet, little millet, proso millet, foxtail millet, lentil, faba bean, chickpea, soybean, groundnut, Indian mustard and gobhi sarson. Of the 2036 varieties of 58 field crops in the current seed production chain, 1425 released during 2019-23 and 796 were inducted in the seed chain during 2024-25 for breeder seed production with variety replacement rate of 56.8, 73.2, 62.8, 67.1 and 20.0%, respectively, for cereals, food legumes, oilseeds, forages and cotton & allied fibres. The impact of new highly released varieties was assessed through the yield enhancement of different field crops. Integration of conventional breeding with molecular breeding is foremost in all crops, but more specifically in minor crops. New approaches like rapid generation advancement, shuttle breeding, speed breeding, double haploidy, *in vitro* haploid production and genomic selection should also be used to accelerate the breeding cycle. Also, there is a need to fast-track the varieties and several new crops for which many varieties have been notified, into the seed chain and develop strategies in view of the large varieties/year is being released.

Keywords: Variety release and notification, Crop breeding, Field crops, Varietal induction, Acreage, Production and yield.

Introduction

The growth of Agriculture and allied sector was 4.7% during 2022-23 at constant (2011-12) basic prices (Anonymous 2024). The crops are the vital components of the Agriculture sector and had a share of 10.3% (2019-20) to 11.3% (2020-21) in the Agriculture and allied sector Gross Value Added (GVA), with growth varying from 2.6% (2020-2021) to 5.7% (2019-20). During 2022-23, the contribution of crops and growth to the Agriculture and allied sector GVA was 10.1% and 4.7%, respectively. Indian agriculture has been witnessing spectacular achievements and scaling new heights in crop production, *viz*., cereals, pulses, oilseeds, sugarcane and jute & mesta except cotton. India, despite natural calamities like the COVID-19 pandemic and erratic

Crop Science Division, Indian Council of Agricultural Research, Krishi Bhawan, New Delhi 110 001, India.

[$]Present address: A/36, ARG Puram, Nayala Road, Kamota, Agra Road, Jaipur 303 012, Rajasthan, India.

[1]ICAR-Indian Institute of Soybean Research, Indore 452 001, Madhya Pradesh, India

[2]ICAR-National Bureau of Plant Genetic Resources, Pusa Campus, New Delhi 110 012, India

***Corresponding Author:** J. S. Chauhan, Crop Science Division, Indian Council of Agricultural Research, Krishi Bhawan, New Delhi 110 001, India, E-Mail: js_chau09@rediffmail.com

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rainfall causing heavy floods and drought in the country, not only sustained agricultural production (Anonymous 2024) but also consistently increased it. India accounted for 11.2% (155.37 m ha) of the global arable land (1387.17 m ha) and ranked second after the USA (Anonymous 2024). India occupied premier position in the world agriculture with 3rd rank in cereal production (11.38%) after China and USA but 2nd in wheat (14.25%) and rice (24.25%) production after China; 1st in pulses (25.88%); 2nd in groundnut (18.5%) after China and 4th in rapeseed (10.01%) after Canada, Germany and China. In the same period, India ranked 2nd in sugarcane (19.87%) after Brazil and also 2nd in jute (48.42%) production after Bangladesh (Anonymous 2024). New high-yielding and climate-resilient varieties are a lifeline for Indian agriculture as they are carriers of the genetic potential of crops. The fact is amply evident by the increase in release and notification of varieties, availability of quality seeds and their reach to the farmers, consequently enhanced seed and variety replacement rates in almost every crop during the recent years (Chauhan *et al*. 2020, 2021a,2022a) and thereby production. The present paper reviews historical aspects of initiation of systematic research in India, varietal status of field crops since implementation of the Seeds Act, 1966, role of private sector in varietal development, induction of recently released varieties in the formal seed chain, impact on crop production and also presents future outlook.

Crop breeding

India has been growing about 60 diverse field crops comprising cereals, pulses, oilseeds, forages, fibres and other potential crops during the last five years. Crop specific breeding programme in cereals, pulses, oilseeds and fibre crops has been initiated at the turn of 20th century especially with the establishment of Imperial Agricultural Research Institute at Pusa, Bengal Presidency during 1905 and five agriculture colleges at Nagpur, Coimbatore, Sabour, Kanpur, Layalpur (presently Faizalabad, Pakistan) during 1901-05 and Pune during 1907 and many other research stations, *viz*., for sugarcane at Pratapgarh (Uttar Pradesh) in 1907 and Sugarcane Breeding Institute (SBI), Coimbatore (Tamil Nadu) in 1912. Jute Agricultural Research Laboratory (JARL) was established in 1938 at Dhaka (undivided Bengal). After partition in 1947, it was shifted to Chinsura and subsequently to Barrackpore, West Bengal and finally to the present location at Nilganj, Barrackpore in 1953 as Jute Agricultural Research Institute (Sarkar et al. 2021). Several earlier publications discussed achievements of 100 years in wheat, pulses, rapeseed-mustard and agricultural research in India (Chauhan et al. 2011; Shoran et al. 2011; Singh et al. 2015; Singh and Singh 2015 personal communication). The crop specific varietal improvement programme has been reorganized in post independent era and currently carried out in the National Agriculture Research, Education and Extension System (NAREES) under the aegis of All India Coordinated Research Projects since 1957 with the establishment of the first All India Coordinated Maize Improvement Project (AICMIP) during 1957 to intensify maize improvement in India; under the Crop Science Division, Indian Council of Research (ICAR), New Delhi. All India Coordinated Crop Improvement Projects (AICCIPs) were renamed as All India Coordinated Research Projects (AICRPs) with the establishment of AICRP on pearl millet in 1965. The success of AICMIP led to the establishment of the 21 AICRPs and 2 All India Network Projects (AINPs) exclusively dealing with crop improvement and seed production research (Chauhan *et al*. 2016a). Since then, with the restructuring and reorganization of research in the ICAR, three AICRPs and one AINP on pulses (Chickpea, Pigeonpea, MULLARP and Arid Legumes) were merged into two and renamed AICRP (Rabi Pulses) and AICRP (Kharif Pulses) and AICRPs on Castor, Linseed, Sunflower and Safflower were merged into one, AICRP on Oilseeds, in 2022 and AICRP-NSP, Seed Project and Breeder Seed production were merged and rechristened as AICRP on Seeds during 2020, and a new AICRP was established for Biotech Crops during 2022. Currently, 19 AICRPs, six AINPs, and seven other networks have been working under the Crop Science Division of ICAR, New Delhi. Of these, 16 AICRPs, three AINPs and three other network projects deal with Crop Improvement and Seed Production research. However, AICRP on Biotech Crops was again renamed as AINP during 2025. The rest, 10 AICRPs/AINPs/other networks are commodity-based / thematic (https://icar.org.in/Crop-Science visited on May 20, 2025), providing a platform for multi-location testing under a range of environments, leading to identification of stable candidate varieties/hybrids. They also strengthen networking partnerships among ICAR institutes, SAUs, Central / State Research Institutes, as well as the private sector. Several main, sub- and voluntary centres have supported each crop-specific AICRP. The network of these centres under AICRPs spreads all over crop-specific agro-climatic zones of the country, which are delineated on the basis of agro-climate and edaphic factors (Chauhan *et al*. 2020, 2022a, 2023a). Seed production, especially breeder seed, has been one of the mandates of AICRPs. The breeding programmes, although, are crop specific but, in general, the focus is on raising ceiling to genetic yield potential, climate resilience, stabilizing yield through up-scaling resistance tolerance of abiotic stresses (extreme temperature, excess/ scanty moisture, edaphic factors, nutrient use efficiency), biotic stresses (weeds, diseases and insect pests), nutritional, cooking and edible quality, using both conventional and molecular approaches.

Output

High-yielding varieties

Chauhan et al. (2016a) and Chand et al. (2020) discussed comprehensively the testing procedure, data collection & analysis, monitoring, identification of candidate varieties/ hybrids under AICRPs as well as states and their release and notification in India. Recently, Chauhan et al. (2025) reviewed the transformed release and notification system of varieties in India and other important policy decisions since the implementation of the Seeds Act, 1966, in 1969 to address the emerging needs to make the quality seed available to the various stakeholders, essentially the farmers, at affordable prices to sustain food security in the country. The various research centres/organizations generate breeding materials and, after testing in station trials for yield and ancillary characters, provide promising genotypes for multi-location testing under crop-specific AICRP. A generalized three-tier model of testing, by-and-large, is being followed for most of the crops under various AICRPs (Fig.1) with some minor crop-specific modifications as with sugarcane (Chauhan et al. 2022b).

After advanced trial II, the varietal idenetification committees under various AICRPs, chaired by Deputy Director General (Crop Science/Horticulture Scence) identify candidate varieties after at least three years of proper rigouros testing of genotypes for seed yield, quality, respone to fertilizers, diseases and pests reaction considering variety for cultivation and use (VCU), either superiority of yield (5%-10%) over the best check (national/ zonal/latest released variety) or resistance to one or more biotic/abiotic stresses, improved nutritional or edible quality or meeting any contingency and availability of adequate breeder seed (Chauhan et al. 2016a). Similarly, the States Sub-Committee on Crop Standards, Notification and Release of Varieties identifies varieties for states.

The official system of release and notification of crop varieties in India has been a legalized system since 1969, after the implementation of the Seeds Act, 1966 and also regulates the quality of seed of varieties. The Seeds Act, 1966 and the Seeds Act, 1972, laid out the framework for variety release and seed certification through the creation of the Central Seed Committee and the Central Seed Certification Board. Therefore, the proposals of identified candidate varieties from various AICRPs and State Seed Sub-Committees are then considered by the Central Sub-Committee on Crop Standards, Notification and Release of Varieties (CSCCSN & RV). The Central Seed Committee then considers the recommendations of the Sub-Committee and recommends to the Central Government to notify varieties in pursuance of section 5 of the Seeds Act, 1966.

Shanmugham and Gunasekaran (2003) reported that 2764 varieties of (69) field crops were notified under Section 5 of the Seeds Act, 1966, from 1966-2002. Chauhan *et al.* (2016b) updated this database and reported that 4357 varieties of 87 field crops, consisting of cereals (14), food legumes (12), oilseeds (16), fibres (5), sugarcane, sugar beet, tobacco, forages (24) and other potential crops (13) have been released until 2015. However, this database did not include several multi-usage (food, fodder, feed, edible and vegetable) crops, especially food legumes such as cowpea, cluster bean, pea, pigeonpea and several potential crops for which varieties are being released and notified separately under Horticultural Crops since 2008. But such varieties were also included in the present database. Further, in the present paper, the release and notification of varieties has been discussed decade-wise to assess the progress of pace of varietal development. The long sustained and ensured

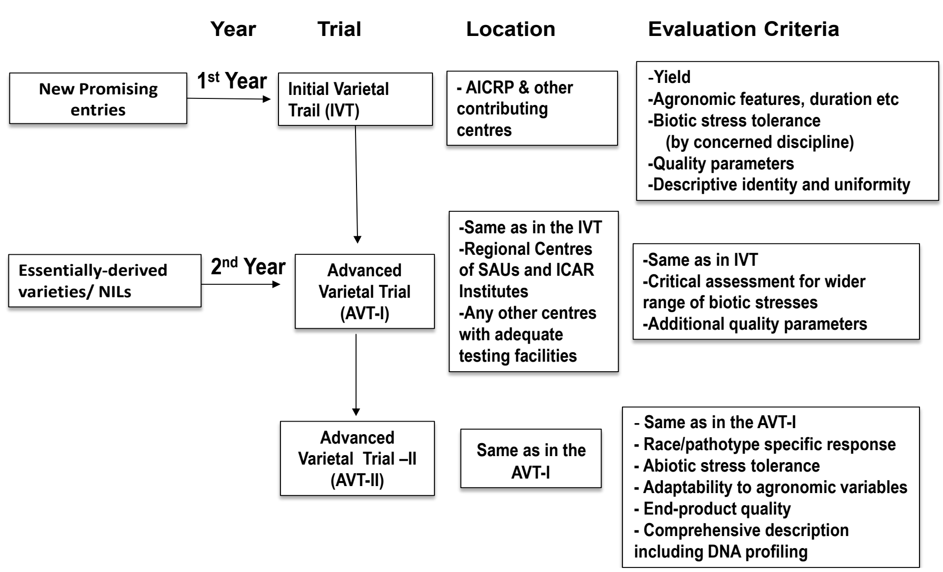

Fig. 1. Testing procedure under AICRPs (Source: Tandon et al. 2015)

vibrant crop improvement programme in various crops over the last 60 years has led to the release and notification of 7488 high yielding, climate resilient, diseases and pest resistant/tolerant varieties/hybrids of 96 crops comprising cereals, food legumes, oilseeds, fibres, sugarcane, sugar beet, tobacco, forages and other potential crops since 1969 until 93rd meeting of Central Sub-committee on Crop Standards, Notification and Release of Varieties for Agricultural Crops held on March 13, 2025 and The Gazette of India, S.O. 2128 (E) dated May 13, 2025 and the Minutes of 32nd meeting of Central Sub-committee on Crop Standards, Notification and Release of Varieties for Horticultural Crops held on April 4, 2025 (F.No.3-77/2025.SD IV, dated April 15, 2025), Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India, New Delhi (www.seednet.gov.in, accessed on June 20, 2025). Among them, cereals have the largest share (48.2%), followed by food legumes (18.9%) and oilseeds (15.4%). There has been a consistent increase in the number of notified varieties since 1969-70 (80) until 2011-20 (1849), except 1991-2000. During first five years of the current decade, 1718 varieties have been released (Fig. 1). Among the various decades, there was consistent increase in the notified varieties since 1969-70 of cereals (from 57–964); food legumes (from 4–303); oilseeds (from 4–263), forages (0–101), fibres (from 15–141) except 1991-2000 when varieties of all the crops released were less as compared to the previous decade (Fig. 1). However, potential crops showed consistent increase in notified varieties since first variety was released during 1971-80 until 2001-10; dipped to 14 during 2011-20 and again went up to 26 (2021-25). Number of varieties released/year across the decades ranged from 40.0 (1969-70) to 184.9 (2011-20), and during the first five years of the current decade, the average number of varieties/year notified was phenomenal (343.6) as compared to the previous decades. This could be due to expansion and empowering NAREES by establishing new institutes/ organizations, reorganizing research programmes, AICRPs and AICRNs under ICAR and state agricultural universities backed by appropriate financial and human resources and a growing dynamic private sector.

Cereals

A total of 3610 varieties of cereals were notified during 1969-2025. Rice crop led the group with the highest number of varieties (44.2%), followed by maize (15.5%) and wheat (15.2%). The share of sorghum, pearl millet and barley was 7.0, 7.0 and 3.0%, respectively (Table 2). Among the six small millets (finger millet, foxtail millet, proso millet, kodo millet, barnyard millet and little millet), finger millet has the largest number of notified varieties with a contribution of 3.5% to the total varieties of the cereals.

Number of varieties released / year consistently increased from 28.5 during 1969-70 to 150.6 during 2021-25 except during 1991-2000 when there was marginal dip (46.2) in comparison to the preceding decade, 47.6 (Fig. 3). It is noteworthy that during the first five years of the current decade, there was greater emphasis on the development of small millets varieties in view of 2023 being the international year of millets and consequently 68 varieties were released and notified. However, in rest of the decades number of small millet varieties released /year ranged from 1(1969-70) to 6.3 (2011-20). Of the total 287 varieties of small millets, finger millet contributed predominantly (43.6%). Further, besides grain, several forage varieties of maize, sorghum and pearl millet were also released and discussed in the forages section.

Food legumes

Of the 18 food legumes, the top contributors to the total (1413) released varieties were three major pulses, *viz.*, chickpea with a share of 20.5%, greengram (14.5%) and pigeonpea(12.5%) and their total share was 47.5% (Table 2). Among the minor pulses and beans, rajmash (56), Indian bean (46), horsegram (31) and moth bean (21) together shared 10.9% of the total notified varieties of food legumes (Table 2). Nevertheless, minor food legumes, including cluster bean, contributed 13.6%. One vegetable variety of pigeonpea (Gujarat Vegetable Tuver 1) was also notified

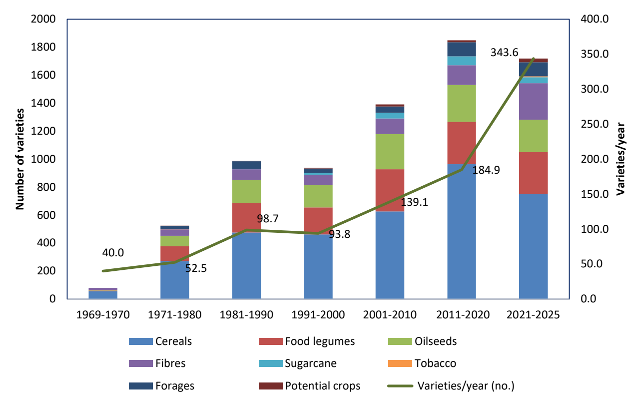

Fig. 2. Total varieties of field crops released and notified with the pace of development during different decades (1969-2025)

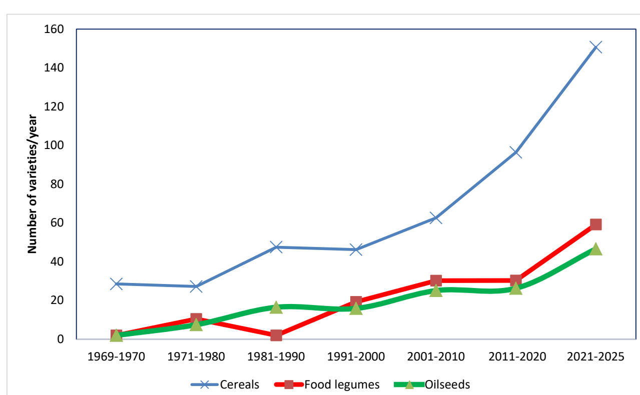

Fig. 3. Number of varieties/year of cereals, food legumes and oilseeds during different decades (1969-2025)

Table 1. Varieties of cereals released and notified during 1969-2025

Crop	Year							Total
	1969-70	1971-80	1981-90	1991-2000	2001-10	2011-20	2021-25	
Rice	18	117	205	192	273	438	352	1595
Wheat	13	60	75	68	102	133	99	550
Maize	16	19	44	67	100	167	147	560
Pearl millet	4	18	32	40	47	78	34	253
Sorghum	3	28	43	42	33	58	46	253
Barley	2	14	14	18	27	26	7	108
Triticale	0	0	2	1	0	1	0	4
Finger millet	1	11	25	16	14	32	26	125
Foxtail	0	3	6	4	4	9	8	34
Proso millet	0	0	7	1	10	4	6	28
Kodo millet	0	0	8	7	5	4	10	34
Barnyard millet	0	0	9	2	5	4	5	25
Little millet	0	2	6	4	6	10	13	41

Table 2. Varieties of food legumes released and notified during 1969-2025

Crop	*Year*							*Total*
	1969-70	*1971-80*	*1981-90*	*1991-2000*	*2001-10*	*2011-20*	*2021-25*	
Chickpea	2	19	42	37	60	62	68	290
Pigeonpea	0	8	37	27	31	40	34	177
Greengram	0	19	33	32	46	42	33	205
Blackgram	0	12	16	27	26	37	32	150
Pea	2	13	15	17	35	36	32	150
Lentil	0	2	10	13	20	32	23	100
Cowpea	0	14	23	10	29	16	16	108
Cluster bean	0	3	8	7	10	2	8	38
Horsegram	0	1	4	5	9	9	3	31
French bean	0	8	6	5	19	7	11	56
Faba bean	0	0	0	1	0	3	6	10
Moth bean	0	1	3	5	7	1	4	21
Indian bean	0	5	11	3	3	7	17	46
Rice bean	0	0	1	2	4	6	0	13
Grasspea	0	0	1	1	2	1	3	8
Winged bean	0	0	0	1	0	1	5	7
Yardlong bean	0	0	0	0	1	0	1	2
Lima bean	0	0	0	0	0	1	0	1

during 1992. Besides grain, forage and vegetable cowpea and cluster bean; vegetable, edible and snow pea varieties were also developed and released. The average number of food legume varieties released and notified per year ranged between 2.0 during 1969-70 to 59.2 during 2021-25, as compared to 30.3 during 2011-20 (Fig. 2).

Oilseeds

Table 3. Varieties of oilseeds released and notified during 1969-2025

Crop	Year							Total
	1969-70	1971-80	1981-90	1991-2000	2001-10	2011-20	2021-25	
Groundnut	1	18	41	39	61	50	33	243
Soybean	2	6	25	24	31	47	58	193
Indian mustard	0	7	16	15	46	42	43	169
Karan rai	0	0	0	2	2	1	0	5
Yellow sarson	0	3	2	4	5	6	3	23
Brown sarson	0	2	0	1	1	4	0	8
Toria	0	5	8	4	4	10	3	34
Tarmira	0	2	0	0	2	4	1	9
Gobhisarson	0	0	1	3	7	2	6	19
Sesame	0	8	26	15	26	16	23	114
Niger	0	0	2	4	10	6	8	30
Safflower	0	5	8	7	9	12	15	56
Sunflower	0	3	10	24	19	16	12	84
Linseed	0	6	19	7	19	31	26	108
Castor	1	10	7	10	9	16	2	55

Table 4. Varieties of commercial crops released and notified during 1969-2025

Crop	Year							Total
	1969-70	1971-80	1981-90	1991-2000	2001-10	2011-20	2021-25	
Cotton	15	37	72	70	85	106	244	629*
Jute	0	7	4	4	16	14	10	55
Mesta -Kenaf	0	0	0	0	4	8	2	14
Mesta-Roselle	0	1	0	0	2	8	3	14
Sunhemp	0	1	0	0	4	3	1	9
Ramie	0	0	0	0	0	1	0	1
Flax	0	0	0	0	0	1	0	1
Sugar beet	0	0	2	0	0	0	0	2
Sugarcane	0	0	0	12	40	63	43	158
Tobacco	0	1	0	0	1	0	6	8

*Including 197 Bt varieties/hybrids

In oilseeds, there were 15 crops for which 1150 varieties were released and notified. Groundnut, soybean, and Indian mustard were the main contributors with a share of 21.1, 16.8, and 14.4%, respectively (Table 3). Rapeseed-mustard, although it had the highest share of 23.1%, is a group of 7 crops. Among this group, Indian mustard, toria, and yellow sarson were the leading crops, having 163, 34, and 23 varieties, respectively (Table 3). Number of varieties among the decades varied from 4 to 263 and varieties released per year ranged from 2 (1969-70) to 46.6 during 2021-25 (Fig. 2). Further, four soybeans (SwarnVasundhra, Karune, NRC188 and Krishna Prabha Pinakini) and three (Narendra Sarson Sag 1, UHF VR 12-1 and Pusa Sag 1) varieties of Indian mustard have been released for vegetable purpose.

Commercial/Industrial crops

Industrial/commercial crops comprise fibres (cotton, jute, mesta (roselle and kenaf), remi, sunhemp, flax), sugarcane, sugar beet and tobacco. Cotton had the largest share (70.6%), followed by sugar crops, *viz.*, sugarcane and sugar beet (18.0%), in the total released and notified varieties of industrial crops (891) during the last six decades (Table 4).

The number of varieties of fibres released per year varied from 7.5 during 1969-70 to 61.8 during 2021-25. The pace of development of varieties of cotton, allied fibres (jute, mesta, ramie, flex) and sugarcane varied between 7.5–48.8/year; 0–3.5/year and 0–8.6/year, respectively (Fig. 4). The AICRP testing of Bt cotton varieties/hybrids also made mandatory prior to their release and first set of such varieties/hybrids was released during 2020. Of the total varieties and hybrids of cotton, 197 were of Bt cotton (31.3%). Only eight varieties of tobacco were released during 1971-80 (1), 2001-10 (1) and 2021-2025(6). Nevertheless, in all, there are 105 varieties of tobacco (ICAR-NIRCA, Rajahmundry, Andhra Pradesh, personal communication, May 20, 2025) released through State Seed Sub-Committees/ Variety Identification Committee of AINP, Tobacco. Apart from 8 notified varieties, the rest can only be termed as extant varieties of common knowledge (VCK) as per the classification of the Protection of Plant Varieties and Farmers' Rights Authority, New Delhi. They were not included in the present database.

Forages

A total of 361 varieties of 27 forage crops were released and notified during the last six decades. Of these, the leading contributor to the total varieties was oats, followed by sorghum, pearl millet and berseem with shares of 19.9, 18.6, 8.3 and 8.0%, respectively, and together contributed 54.8% (Table 5). The number of varieties released per year during different decades ranged from zero during 1969-70 to 20.2 during 2021-24 (Fig. 4).

Potential crops

Thirteen potential crops that are rich in nutrients, minerals and nutra-ceuticals as well as having tolerance of abiotic stresses, thus climate resilience, but, grown presently on a very limited scale in certain pockets. However, they hold promise in the future to become major crops as they are the reservoirs of useful gene resources for nutritional quality and tolerance of diverse stresses to mitigate the challenges of climate change in the years to come and offer scope for diversifying food and sustaining the food production system. Of the 63 varieties of potential crops, amaranths have the largest varieties released and notified (Table 6).

Bio-fortified varieties

Improvement of nutritional quality was initiated as early as the late 1960s or early 70's in many crops (Chauhan et al. 2011; Yadav et al. 2015). In maize, protein is nutritionally poor due to low content of essential amino acids, tryptophan, and lysine. The discovery of a recessive allele *opaque* 2 (*o2*) that increases tryptophan and lysine amino acids by 2-3 fold led to an intensive introgression programme to incorporate the *o2* allele into elite genetic background and resulted in the release of three *o2* maize composites, Shakti, Rattan and Protina in 1971 (Yadav et al. 2015). But, due to the chalky appearance of grains and the negative pleiotropic effects of *o2,* like soft endosperm resulting in high damage to storage insects, these could not become popular. Research efforts at CIMMYT, Mexico, led to hard endosperm-based *o2* by combining desirable endosperm modifiers. Accumulation of modifiers, particularly from CIMMYT germplasm, led to the development of Composite Shakti 1, the first hard endosperm-based *o2* released in India during 1997 and the first quality protein maize hybrid, Shaktimam 1, was released in India in 2001 and later Shaktimam 2 (2004), Shaktimam 3 and Shaktiman 4 (2006) and Shaktimam 5 in 2013 (Yadav et al. 2015) and first bio-fortified pearl millet composite, Dhanshakti, was released in 2014 and 11 more nutrient-rich cultivars were released (Yadav et al. 2024). Breeding for developing rapeseed-mustard varieties with low erucic acid (< 2.0%) in oil, called zero (0) and low glucosinoloates (< 30 micromoles of glucosinolate/g of defatted seed meal), called zero (0) and combining both the traits resulting into double zero (00) was initiated in early 1970's and the first low erucic acid Indian mustard variety, Karishma was released in 2005 (Chauhan *et al*. 2011) followed by Pusa Mustard 21, RLC 1 (2007), Pusa Mustard 22 (2008), Pusa Mustard 24 (2009), Pusa Mustard 29, Pusa Mustard 30 (2013) and first double low variety, Pusa Double Zero 31 was released in 2016 (Chauhan *et al*. 2021). Further, in gobhi sarson, first double low variety, GSC 5 was released in 2005, followed by GSC 6, NUDB 26-11 and TERI-Uttam-Jawahar in 2008 (Chauhan *et al*. 2021).In recent years, for addressing the challenges of malnutrition, besides amino acid tryptophan, lysine and provitamin A, protein content, high oleic acid, lowering anti-nutritional factors like erucic acid and lucosinolates content, greater emphasis is also being laid on micro/macro-nutrients (zinc, iron, calcium). Concerted efforts led to the development of 170 bio-fortified varieties of 16 field crops (Yadava *et al*. 2023; Sharma et al. 2025; personal communication, ICAR, New Delhi) comprising rice (15), wheat (73), maize (32), barley (1), pearl millet (13), finger millet (7), little millet (2), proso millet (1), foxtail millet(1), lentil (3), chickpea (1), faba bean (1), Indian mustard (8), gobhi sarson (1), soybean (8) and groundnut (3)

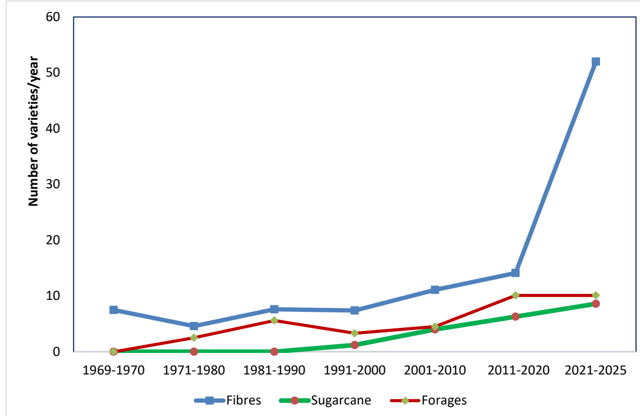

Fig. 4. Number of varieties/year of sugarcane, fibres and forages released during different decades (1969-2025)

Table 5. Varieties of forages released and notified during 1969-2025

Crop	Year							Total
	1969-70	1971-80	1981-90	1991-2000	2001-10	2011-20	2021-25	
Oat	0	6	6	2	7	26	25	72
Berseem	0	3	5	2	4	4	11	29
Pearl millet	0	1	2	2	1	7	17	30
Sorghum	0	2	12	7	5	16	25	67
Maize	0	0	1	1	0	1	10	13
Teosinte	0	0	0	1	0	0	0	1
Cowpea	0	5	2	4	5	6	3	25
Cluster bean	0	1	4	3	1	1	0	10
Lucerne	0	2	4	2	1	5	5	19
Buffel grass	0	0	2	1	1	5	0	9
Birdwood grass	0	0	1	0	0	3	0	4
Guinea grass	0	0	4	3	4	3	0	14
Fescue grass	0	0	0	1	2	1	0	4
Sudan grass	0	2	0	0	0	0	0	2
Marvel grass	0	1	0	0	1	4	0	6
Dinanath grass	0	0	3	1	0	0	1	5
Setaria grass	0	0	3	0	1	2	0	6
Rye grass	0	0	0	0	0	2	0	2
B x N Hybrid	0	0	4	1	6	8	2	21
Aparajita	0	0	0	0	0	1	0	1
Vicia	0	0	0	0	0	1	0	1
Sewan grass	0	0	0	0	0	2	0	2
Sen grass	0	0	0	0	1	0	0	1
Sesbania	0	0	0	0	2	0	1	3
Hedge lucerne	0	0	0	0	0	2	0	2
White clover	0	0	1	0	0	0	1	2
Persian clover	0	0	0	1	0	0	0	1
Sweet clover	0	2	1	1	0	0	0	4
Bajra x Squamulatum	0	0	0	0	0	1	0	1
Red clover	0	0	0	0	1	0	0	1
Styloxanthus	0	0	0	0	1	0	0	1
Dharaf grass	0	0	1	0	1	0	0	2

since 2014 until The Gazette of India, S.O. 2128 (E) dated May 13, 2025. However, several varieties released after 2014 of Indian mustard, *viz*., RLC 2, RLC 3 (2016) and BPM1825 [DMR CI Q (47)] in 2025 and gobhi sarson such as GSC 7 (2015), PGSH 1707 (2021), PGSH 2155 (2024), high linoleic acid variety TL 99 (2019) of linseed and high oleic acid (76.0%) variety ISF 1/Pride of safflower (2019) (Chauhan *et al*. 2021) and five maize hybrids/varieties (HPQM1, HPQM5, HPQM7, HPQM4 and Pratap QPM Hybrid 1) having high lysine and tryptophan amino acids were missing from this database.

Molecular breeding

Besides conventional breeding, which was the main contributor to the development of >99.0% of the released varieties, molecular breeding has been pursued in India since the 1980's which led to the release and notification of

Table 6. Varieties of potential crops released and notified during 1969-2025

Crop	Year							
	1969-70	1971-80	1981-90	1991-2000	2001-10	2011-20	2021-25	Total
Amaranths	0	1	2	1	8	7	16	35
Buckwheat	0	0	0	4	3	0	0	7
Jatropha	0	0	0	0	1	0	0	1
Kalingda	0	0	0	0	0	1	2	3
C. alba (Bathua)	0	0	0	0	0	5	0	5
C. quinoa (Bathua)	0	0	0	0	0	0	1	1
Asalio	0	0	0	0	0	0	3	3
Job's tear	0	0	0	0	1	0	0	1
Babchi	0	0	0	0	0	1	0	1
Perilla	0	0	0	0	0	0	1	1
Brown Top Millet	0	0	0	0	0	0	2	2
Kankoda	0	0	0	0	1	0	1	2
Tumba	0	0	0	0	1	0	0	1
Total	0	1	2	5	15	14	26	63

Pusa Jaikisan (BIO 902), a somaclone of the mega mustard variety, Varuna, during 1993. Further, the cytoplasmic male sterility system (*mori*) has been developed through repeated backcrossing of the somatic hybrid developed by protoplast fusion of *Moricandia arvensis (2n=28, MM)* and *Brassica juncea* (2n=36; AABB) to *Brassica juncea*. The restorer (MJR 15), *mori* CMS *B. juncea* and fertility restored F_1 plants possess similar cytoplasmic organellar genomes (Prakash *et al*. 1998). *Ogura* (*ogu*) cytoplasm of *Raphanus sativus* conferring male sterility has been transferred to *Brassica juncea* following a cell fusion approach in India (Kirti *et al.* 1995). It was done in two steps; first, *ogu* cytoplasm was transferred from male sterile *B. napus* to *Brassica juncea* cv. RLM 198 through repeated back crossing and selection. Thereafter protoplast of male sterile *B. juncea* was fused with normal RLM 198 to rectify defects such as high chlorosis, lateness, low seed fertility and small contorted pods. The putative cybrids having recombinant mitochondria were again backcrossed with RLM 198, resulting in chlorosis-corrected plants with early flowering and improved seed fertility (Kirti *et al*. 1995). These two systems, after further refinement and transfer to elite germplasm of *Braasica juncea* were extensively used in the national rapeseed–mustard improvement programme. First hybrid of Indian mustard, NRCHB 506 was released during 2009 using *mori* CMS system. Later, *ogu* CMS based hybrids of Indian mustard, Coral PAC 432 (2010), Coral PAC 432(2012), SVJH 108, RCH 1 and PHR 126 (2021) were released and notified. There is another hybrid of Indian mustard (DMH 1) released during 2009 using CMS 126-1 system. In gobhi sarson, hybrids, Hyola 401 (1997), PGHS 1699 (2021), PGSH 1707 (2021) and PGSH 2155 (2024) are *ogu* CMS based. Hybrid PGSH 51 was developed in 1996 using *tournefortii* (*tour*) CMS system.

The *Barnase* gene derived from *Bacillus amyloliquefaciens* induced male sterility was first reported my Mariani et al. (1990) and applied in rapeseed (*Brassica napus*) by Chinese researchers (Zhou et al. 1997) for hybrid development. The system involves transgenic lines containing the *barstar* gene encoding *barstar,* an intracellular inhibitor of the ribonuclease, *barnase,* both from *Bacillus amylolique* bacteria, have been used to develop a complete male sterility/restoration system for hybrid breeding. In India, a new technique to identify male-sterile-restore combination using *barnase-barstar* gene system for heterosis breeding was developed in Indian mustard (Bisht et al. 2007; Ray et al. 2007). Using this system, an Indian mustard hybrid (DMH 11) was developed by Delhi University South Campus, New Delhi. Nevertheless, a more focused approach in molecular breeding, such as the use of molecular markers in gene identification, tagging of markers with phenotypic characters, identification of introgression of genes in repeated backcrossing and marker-assisted selection (MAS) in segregating generations was first initiated in 2000 in India with rice and maize crops. Currently, molecular breeding in India has been targeting at eight crops (rice, wheat, maize, pearl millet, chickpea, lentil, soybean and groundnut) for improving 20 traits comprising nutritional and other quality traits (amino acid tryptophan, lysine and pro-vitamin A in maize, high oleic acid in groundnut), nutrient use efficiency (low phosphours), earliness in soybean, herbicide tolerance in rice, tolerance of biotic (bacterial blight, blast in rice; stripe rust and leaf rust in wheat; downy mildew in pearl millet; *Fusarium* wilt in chickpea and YMV in soybean); abiotic stresses (drought, salinity and submergence in rice; drought in chickpea), removing/lowering the undesirable traits such as Kunitz tripsin inhibitor (KTi3) and less beany flavour in soybean. In India, the pearl millet hybrid, HHB 67-Improved, having downy mildew resistance, was the first MAS-derived variety released in 2005. Similarly, the first released MAS-derived varieties in other crops were Improved Pusa Basmati 1 (2007) with bacterial blight resistance; Vivek QPM 9 (2008) having high levels of essential amino acids, tryptophan and lysine; PBW 723 (2017) with resistance to stripe and leaf rusts; NRC 127 (2018), having KIT free trait; Pusa Chickpea 10216, Super Annigri 1 (2020) having *Fusarium* wilt resistance and Girnar 4 and Girnar 5 (2020) with enhanced level of oleic acid of rice, maize, wheat, soybean, chickpea and groundnut, respectively (Yadav et al. 2015; Gopalakrishnan et al. 2025). Concerted and well coordinated programme since 2000 have led to the release and notification of 122 varieties consisting of rice (65), wheat (8), maize (23), pearl millet (2), chickpea (9), lentil (1), soybean (11) and groundnut (4) (Gopalakrishnan et al. 2025; personal communication, ICAR, New Delhi) during 2014-25 (The Gazette of India, S.O. 2128 (E) dated May 13, 2025). Further, during 2023, three Indian mustard varieties, Pusa Bold WRR 2, Varuna WRR 2 and Rohini WRR 2 were released using MAS for white rust resistance. Delhi University South Campus, New Delhi, developed these.

Hybrids

Hybrids are known to outperform varieties in yielding ability and have been developed predominantly in cross-pollinated crops such as maize, pearl millet, sorghum, cotton, sunflower, castor and gained wide acceptance among the farmers/growers since their release and played a very important role in yield enhancement, consequently, production in India. The Indian Council of Agricultural Research launched a national programme for the development and widespread adoption of hybrid rice in December 1989 with the primary goal of bringing about 25% rice acreage under hybrid by 2015 (Spielman et al. 2013) and the first (KRH 1) hybrids was released in 1996 followed by APHR1, APHR2 and MGR1 (CORH1) in 1997. Since then, systematic and concerted efforts have resulted in the release of about 162 hybrids of rice consisting of 115 central and 47 State release of total hybrids, 44 were developed by public sector organizations (Source: IIRR, Hyderabad, 2025). Further, 'ICAR Project on Development of Hybrids' was also launched during 1989, which covers several crops including pigeonpea and rapeseed-mustard, leading to the development of several promising CMS based hybrids of pigeonpea and rapeseed-mustard.

The success of hybrid technology depends largely on the extent of heterosis, the availability of an efficient male fertility circumvention system, robust seed production technology, capacity building for hybrid seed production and effective marketing strategies. Further, easy accessibility of technology, cost of inputs (seed), overall production and significant gains over and above the best available one are pivotal for successful hybrid technology. The relatively low level of heterosis of 10 to 20% at farmers' fields (Spielman et al. 2013) may not be enough to justify the higher seed cost of hybrids is the primary reason for the limited popularity of hybrids in rice, Indian mustard and pigeonpea. Farmers prefer to use the high-yielding inbred or pure line varieties instead of purchasing hybrid seed every year. Other economic barriers like low benefit: cost ratio and social factors like the traditional farmer seed saving, varietal attributes, including plant height, seed weight, disease resistance, maturity and grain or oil quality, also influence farmers' choices and often make hybrids less preferable. Moreover, limited private investment and weak seed dissemination systems are the major deterrents to the success of hybrid technology in these crops. Public-sector hybrids, in particular, often suffer from problems in quality seed production and marketing.

Complexities in hybrid seed production in these crops require strict isolation, maintenance of parental lines and skilled management, but the seed yield is often low, further raising costs. Seed production needs enforced cross-pollination, achieved through cytoplasmic male sterility, chemical hybridizing agents, or manual emasculation. In rice, most of the WA based CMS lines have mperfect panicle exsertion and 15 to 20% spikelets remain enclosed in the flag leaf and thus not exposed to out-crossing necessitating application of 45 to 60 g/ha GA3 in two splits and flag leaf clipping to promote panicle exsertion and also supplementary pollination either by rope pulling or by shedding the pollen parent with the help of two bamboo sticks to increase the extent of out crossing (Verma *et al*. 2021) all are technically challenging, labor-intensive and further escalate seed production cost. In view of sensitive technical requirements such as careful management of breeding materials, the hybrid seed production, unlike varietal rice, is difficult to entrust to various seed production models prevalent in India, like community or village level seed production schemes, smallholders, farmer producing cooperatives or organizations (Spielman *et al*. 2013). In pigeopea, Saxena et al. (2025) also highlighted seed production problems in GMS-based hybrids, ICPH 8, from ICRISAT, such as uprooting of 50% fertile plants because segregation of hybrid seed into fertile and sterile plants is essential, and intensive rouging within the female rows is not practical in large seed production plots. Thus, in spite of a high seed yield advantage, the hybrid was not successful. Many CMS based hybrids in pigeonpea, *viz*. ICPH 2671 (2014), IPH 09-5 (2020), IPH 15-03 (2019), Pusa Hybrid

Arhar 5 (2023) were also released and notified, but due to hybrid seed production difficulties like failure to conduct grow-out test (GOT) to know the level of genetic purity of seeds due to photoperiod-sensitivity of the hybrids that prevents growing of follow-up generation to ensure genetic purity. Because of this, seed companies did not accept the pigeonpea hybrids technology despite a high level of yield advantage. They suggested that early maturing hybrids where GOT is possible should be developed. Further, the possibility of using DNA markers for testing the genetic purity of seed may be explored.

Of late, pigeonpea and rapeseed-mustard hybrids are also under cultivation with varying levels of success on very limited acreage. However, the hybrids of pigeonpea did not attain the perceived success among the farmers and rapeseed-mustard hybrids are yet to find a visible place in the seed production chain. Spectacular success was achieved in India for castor and sunflower because of strong heterosis, efficient hybrid seed production systems, oil quality retention and strong market demand. Sunflower, currently, even as a crop, has been facing serious challenges as its acreage declined drastically by 93.6% to just 0.15 m ha (2023-24) from the highest ever achieved (2.34 m ha) during 2005-06 (Anonymous 2024). Shrinking acreage of sunflower is attributed to moisture stress and high temperature (especially during the reproductive phase), further compounded by erratic rainfall trends and climate changes in major growing areas in north-western states, Karnataka, Andhra Pradesh and Telangana. Increased complex of diseases and insect pests' outbreaks, lack of access to quality inputs (seed) at affordable prices and poor marketing facilities were the other important factors leading to declining acreage. This crop is also facing the challenge of crop substitution with maize during summer in north-western states due to market-driven forces for the possible use of maize in ethanol production. And, also competition from other oilseeds such as soybean and groundnut makes sunflower cultivation less remunerative now. Safflower has very limited acreage of about 50,000 ha. Despite this spectacular achievement, anticipated success in their adoption by farmers was not achieved. Because of certain issues like low level of heterosis, grain quality and high seed cost; adoption of rice hybrid technology is about 7% viz., 3.5 mha in the total rice acreage of 47.82 mha during 2024 (Source: IIPR_ and for away from the good set in 1989. Further, the hybrid seed requirement for rice declined consistently and considerably since 2020-21 by 33.4, 45.2, 50.0 and 44.1% during 2021-22, 2022-23, 2023-24 and 2024-25, respectively (Anonymous 2024).

Since farmers in India commonly save their seed, and varietal purity in self-pollinated crops can be maintained for several generations, the incentive to purchase fresh hybrid seed each season is low. Unlike maize, where private companies release many hybrids with attractive traits, the number of hybrids in pigeonpea or rice is limited and not available across all the agro-ecological regions. Because seed replacement each year is not required, the hybrid seed business in self-pollinated crops is less profitable, discouraging private sector investment. As a result, most hybrid development efforts in mustard, rice, and pigeonpea are led by public institutes that face resource and extension limitations.

Poor grain quality of hybrids, which initially led to a low level of consumer acceptance, particularly in high-productivity irrigated regions where market surpluses are produced is less in rained and low productivity region (Spielman et al. 2013) has now declined substantially due to improved grain and cooking quality of recently released hybrids. Similarly, diversifying the genetic base for improving heterosis level for yield and grain quality was also suitably addressed by several international and national programmes, including India through the Hybrid Rice Development Consortium, a global platform initiated in 2008, sharing 7400 germplasm samples among the hybrid rice researchers (Spielman *et al*. 2013). Despite all these concerted efforts, a low level of heterosis, a narrow genetic base of released hybrids largely based on single WA cytoplasm and grain quality in rice, a daunting task to satisfy consumers' preferences of diverse regions, are still the real challenges in the adoption of rice hybrids, for instance, consumers demand specific grain types with desirable cooking quality and aroma. Many rice hybrids fail to match the grain quality of popular varieties such as Basmati or Samba Mahsuri despite higher yields, limiting their adoption. Yield instability across environments, high input-demand and sometimes increased vulnerability to stresses of rice hybrids discouraged farmers from going for hybrid technology. Lack of strong institutional mechanisms for production and of hybrid seed of public sector developed hybrids further makes the spread of hybrid rice technology challenging.

Several Indian mustard and gobhi sarson hybrids have been grown on limited acreage in certain pockets of Punjab, Rajasthan, Uttar Pradesh and Madhya Pradesh. In CMS derived Indian mustard hybrid, the reduced seed size in comparison to improved varieties deters their adoption despite higher seed and yield, as is the case with DMH 1. However, a genetically engineered mustard hybrid (DMH 11) developed about 20 years back, despite outperforming all the standard checks substantially, could not see the light of day because of regulatory hurdles and public outcry about GM crops, which have slowed acceptance and scaling of such hybrids. In pigeonpea, large-scale hybrid seed production remains difficult due to variability in natural cross-pollination as mediated by a variety of foraging insects. Broader adoption in these crops will require breakthroughs in heterosis expression, grain and oil quality improvement, seed production efficiency and stronger public-private partnerships.

Overall, during 2019-20 to 2024-25, the contribution of hybrid seed to the total seed requirement (19.4-22.61 lakh q) and availability (21.8–26.0 lakh q) of field crops was 6.7 and 7.2%, respectively, during 2019-20, the corresponding values declined to 6.2 and 5.6%, respectively, during 2024-25. Contribution of maize, rice, pearl millet and sorghum was 40.0–54.8%, 15.7–30.4%, 9.6–11.0% and 5.1–7.3%, respectively, to hybrid seed availability during 2020-19 to 2024-25. Cotton had a share of 8.0–13.1% in total hybrid seed availability during the corresponding period. Other crops (sunflower, safflower, pigeonpea and castor) had a very low share of <1–4.4% during 2019-20 to 2024-25.

Among the total varieties/hybrids released in India, 24, including 23 imported ones, were released provisionally for two years and six varieties from Bangladesh for three years for Bihar and West Bengal. Since 2011, when varieties were again notified for specific state/s, of the total 3567 released varieties, 1935 (54.25%) and 1632 (45.75%) were central (more than one state) and state varieties, respectively. Further, there has been a phenomenal increase in the number of released and notified varieties from the private sector as of the 604 total released varieties, 521 were released during 2011-2025 contributing about 17.0% to the total released and notified varieties during 2011-25 (Fig.5). And, their share increased over the years from 12.4% (2011-20) to 17.05% (2021-25). Among the total varieties released by the private sector, cereals and industrial crops had a share of 57.0 and 31.2%, respectively. The private sector predominantly contributed (83.8%) to the total Bt varieties/hybrids of cotton released in India.

Outcome

Outcome of the field crops breeding was assessed by trends in varietal replacement in the seed production chain and current trends in crop acreage, production and yield *vis-a-vis* 1969-70, the year when the Seeds Act, 1966, was implemented.

Dynamic seed production chain

Development and release of varieties is of no consequence unless inducted into the seed production chain to make available seed to the farmers. Indent for breeder seed production is the beginning of the formal seed production chain. To assess variety replacement by recently released varieties (2019-23), the seed production chain for the year 2025-26, *viz*., varieties intended for breeder seed production during 2024-25, was analyzed with their contribution to the total breeder seed indent.

Among the cereals, of the 96 released varieties of wheat, 71 were in the seed chain, suggesting that 74.0% of the total varieties were in the seed chain, accounting for 67.4% of the total breeder seed indent. Also, 13 varieties released during 2024, accounting for 6.1% of the indent, were in the seed chain. In barley, of the seven varieties released during the last five years, six were inducted in the seed chain with a very low contribution of 7.3%. In rice, only 60.5% (193) of the recently released varieties (319) were in the seed chain and accounted for only 32.7% of the total crop indent. Two varieties released during 2024 just contributed 0.04%.

Of the 103 maize varieties and hybrids released during 2019-23, only 28 (27.2%) were inducted in the seed production chain accounted for 63.2% of the breeder seed indent. Also, two varieties/hybrids of maize released during 2024 accounted for 0.26% of the breeder seed indent. Pearl millet also had a low varietal replacement rate of 33.3% as only 11 of the 33 varieties and hybrids were in the seed chain and their contribution to breeder seed was moderate (46.4%). Of the 40 released varieties hybrids/varieties of sorghum, 23 were in the seed chain (57.5%) and contributed 69.1% to the seed indent. A high varietal replacement of 66.7% was observed for finger millet, as 16 of the 24 varieties were in the seed chain, having a contribution of 46.7% to the seed indent.

In chickpea, 47 of the 65 varieties (72.3%) recently released varieties were inducted in the seed chain with a contribution of 52.5%. Furthermore, nine varieties released during 2024 contributed 5.1% to the breeder seed indent. Contribution of recently released varieties was substantial (57.2%) and about 82.9%, 31 out of 41 recently notified varieties were in the seed chain of pigeon pea. Contribution of varieties released during the last five years was high for blackgram, 70.5%, as 38 out of 41 recently released varieties (92.7%) were in the seed chain and low for greengram, 34.6%, despite the fact that 92.3% (24 out of 26) varieties released during the last five years were in the seed chain. In lentil, 79.2% of newly released varieties (19 out of 24) were in the seed chain, contributing 55.4% to the seed indent. One lentil variety released during 2024 was also in the seed chain, having only a 0.5% share. The contribution of recently released varieties of cowpea was very low, 3.4%. Nevertheless, 75.0%, nine out of 12 varieties, were inducted in the chain. Varietal induction of cluster bean in the seed chain was 75%. Thirteen varieties out of 16 of peas released during 2019-23 were in the seed chain, contributing 59.0% to the seed indent.

In soybean and groundnut, 73.7% (42 of the 52) and 91.7% (33 of the 36) of the recently released varieties, respectively, were in the seed chain with a share of 52.2 and 63.0%. Despite the induction of 77.4% of the newly varieties of Indian mustard (24/31) in the seed chain, their contribution was only 44.7%. For Toria, the varieties notified during the last five years had a share of 45.4% in the breeder seed indent and all the varieties (6) were in the seed chain. In yellow sarson, three varieties were notified during 2019-23, all were in the seed chain, but their contribution was very low (17.9%) in the seed indent. Fifteen of the 17 recently released varieties (88.2%) of sesame accounted for 70.4% of the seed indent. In castor, two varieties among the six notified during 2019-23 contributed 30.6% to the seed indent.

Of the 22 varieties of oat released during the last five years, 16 (72.7%) were in the seed chain, sharing only 27.6% of the breeder seed indent. One oat variety released during 2024 contributed 0.5% to the breeder seed. In berseem (8), lucerne (3) and maize (4), all the recently released varieties in the seed chain accounted for 51.4%, 32.9% and 27.7%, respectively, of the seed indent. In sorghum, 11 of the 17 recently released varieties (64.7%) accounted for 52.1% of the breeder seed indent. Ten of the 12 varieties/hybrids of bajra notified during 2019-23 were in the seed chain, contributing 79.8% to the crop indent of breeder seed.

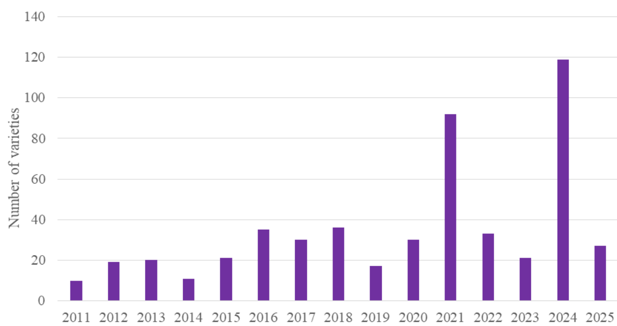

Fig 5. Varieties of field crops developed by the private sector during 2011-25

Cotton and jute are the major fibre crops. The major cotton area has been under Bt cotton (> 90%) for the last 10 years and seed production of Bt cotton is largely in the private domain and does not fall under the purview of the formal seed chain. Nevertheless, public sector accounted for about 16.6% of the total Bt-notified varieties/hybrids in India. Overall, 32 varieties/hybrids from public sector organizations contributed 39.0% to the seed indent. In jute, 62.5% (5) of the total notified varieties (8) shared 58.5% of the breeder seed indent.

Apart from the various major crops for which analysis of breeder seed indent was carried out, there are many crops, *viz*., small millets, minor food legumes, oilseeds, forages & grasses and allied fibres grown on very small acreage or still not in the formal seed production chain. Considering both major and minor crops together, were total of 657, 261, 215, 82 and 210 varieties of cereals, food legumes, oilseeds, forages and allied fibres, respectively, were released during 2019-23. Overall variety replacement was 56.8, 73.2, 62.8, 67.1 and 20.0%, respectively, for cereals, food legumes, oilseeds, forages and cotton and allied fibres.

Crop acreage, production and yield

There has been a quite significant surge in production and yield of field crops during the last six decades (Table 7). Food grains production increased by 235.3% with concomitant increase in yield by 212.7% with only 6.9% change in cropped area during 2023-24 as compared to that of 1969-70 (Table 7). An increase of 252.6% was achieved largely because of the spectacular yield enhancement of 242.2% as there was a marginal increase of 3.0% in acreage for cereals. However, in comparison to 1969-70, pulses acreage increased substantially during 2023-24 by 24.9% with corresponding enhancements of 107.9 and 65.9%, respectively, for production and yield (Table 7).

The oilseeds cropped area was doubled, with more than five times increase in production and 2.5 times higher yield during 2023-24 than that of 1969-70. Similarly, sugarcane cropped area was doubled; production tripled and yield was higher by 160.7% during 2023-24. There was a spectacular yield enhancement of 144.4% for jute & mesta during 2023-24, accompanied by a 42.6% increment in production with appreciably reduced acreage by 41.3%. Nevertheless, it is worth mentioning that yield enhancement depends on a number of genetic and non-genetic factors like variety, seed, integrated crop management technology, market intelligence and opportunity for product surpluses at remunerative prices and government policies to incentivise crop/s. However, the use of both high-yielding varieties coupled with good quality seed has been reported to

Table 7. Area [A], production [P] and yield [Y] of field crops during 1969-70 and 2023-24

Crop	1969-70			2023-24		
	A (m ha)	P (m t)	Y (kg/ha)	A (m ha)	P (m t)	Y (kg/ha)
Food grains	123.57	99.50	805	132.1	332.3	2515
Cereals	101.55	87.81	865	104.6	308.0	2945
Pulses	22.02	11.69	531	27.5	24.3	881
Oilseeds	14.81	7.73	522	30.2	39.7	1314
Cotton	7.73	0.95	122	12.7	5.5	436
Jute & Mesta	1.09	1.22	1120	0.64	1.74	2737
Sugarcane	2.75	135.02	49121	5.7	453.2	79.0

enhance yield by up to 40.0%. Several earlier studies (Chauhan *et al*. 2016c, 2020, 2021a, b, 2022a, 2023, 2024) reported that high variety and seed replacement rates in cereals, pulses, oilseeds and forages seemed to be the major reason for yield enhancement.

Nutritional security

Over 170 bio-fortified varieties of 16 field crops have been developed, which are assets to minimize the risk of malnutrition. But they need to be fast-tracked in the seed production chain for large-scale production and food product development. Since they are the value-added varieties, their seed production should be undertaken in a special seed multiplication programme and should be incentivized. But this adventure needs a strong public-private linkage, especially for food product development. An appropriate awareness programme about the health benefits of such varieties to create demand for consumption should be undertaken. The KIT free soybean varieties have already been licensed to the private sector, but, approach should be to foster linkages and partnership development. The possibility of replicating initiatives like Nutri-Hub under the ICAR-IIMR, Hyderabad (Yadav *et al*. 2024) for bio-fortified varieties should also be explored to accelerate their commercialization. Several bio-fortified varieties of rapeseed-mustard developed for seed and meal quality and seed meal released as early as 2005 did not commercialize due to problems in maintaining the traits in the subsequent stages of seed production and being grown as a normal crop just for seed and oil yield. Nevertheless, it is too early to assess the impact of such varieties in other crops.

Future outlook

To increase farmers' income and alleviate malnutrition, crop breeding should focus on climate resilience, nutritional quality, coupled with yield increase. Greater focus should be on disadvantaged crops, minor pulses & beans (food legumes), minor cereals (small millets) and minor oilseeds (niger, linseed and safflower) since these crops are well adapted and climate resilient and can be grown in diverse, fragile agro-ecological environments in diverse cropping systems as pure or mixed crops. Further, minor food legumes such as moth bean, horsegram, cowpea, cluster bean, French bean, rice bean, faba bean, Indian bean and winged bean are rich sources of proteins; some of them have multiple uses such as grain, vegetables and/or fodder/feed. Nevertheless, the International Year of Minor Millets in 2023 created a lot of awareness about millets, especially minor millets, amaranths and buck wheat. These crops were designated as 'Shree Ann'; the momentum should not only be sustained but further vigorously pursued, and research efforts should be backed by appropriate financial/human resources and linked to industry to develop entrepreneurship. A similar approach should be adopted for minor food legumes. There is also a need to evaluate the bioavailability of enhanced levels of nutrients among the bio-fortified varieties in a well-designed, systematic programme to prove their worth. Shree Ann, minor food legumes and other bio-fortified crop varieties should also be included in the government's public distribution system to alleviate malnutrition. Raza et al. (2025) suggested that in future crop breeding programmes, the spatial heterogeneity of soils should also be considered, as evolving dynamics of soils greatly impact the optimal yield performance of the genotypes. They further opined that soil metrics should be the essential criteria for evaluating crop genotypes along with yield, disease, insect pests, and abiotic stress resistance/tolerance to develop high-yielding varieties. In multi-location yield evaluation trials under AICRPs, there should be necessary changes in the criteria to identify candidate variety/ies not only for irrigated/rainfed/drought/salinity/heat stresses agro-ecosystem but also for specific soil conditions to harness their optimal yield potential. Molecular breeding has been successfully employed to develop varieties in all major crops; the same should be vigorously pursued in minor crops also. Thus, integration of conventional breeding with molecular breeding is foremost in all crops, but more specifically in minor crops. To accelerate the breeding cycle, new approaches like rapid generation advancement, shuttle breeding, double haploidy, *in vitro / in vivo* haploid production and genomic selection should also be deployed (Sharma et al. 2022; Singh et al. 2022). Singh et al. (2022) discussed the success of some of these approaches in oilseed Brassicas.

Recently, two gene-edited varieties of rice, *viz*., Kamala in the background of mega variety, Samba Mahsuri (BPT 5204) and Pusa DST Rice 1 in the background of another mega variety, Cotton Dora Sannnalu (MTU 1010), were launched in India (Choudhary and Mayee, 2025a). Since their launching, a lively debate ensued, starting with opposition by environment activists such as Coalition for GM-free India on the basis of ill-founded apprehensions and again labeled it as a backdoor entry of GM crops in India despite the fact that no foreign/ exogenous DNA was utilized in these gene-edited rice varieties. Choudhary and Mayee (2025a) analyzed the various hurdles faced by the use of biotechnological approaches in crop improvement since the release of the first BT cotton in 2002, which led to a lack of interest among the private sector for investment and slowed the pace of biotech-based innovation, in general, and more specifically in cotton. They also presented a comparison between genome editing, transgenic genetic modification and comprehensively discussed the extant regulatory framework for genome editing in India. They were quite optimistic that the approval of gene-edited rice, a strategic and science-led policy change, would lead to accelerated product development in other crops. This successful launch of genome-edited rice varieties may serve as a game changer not only in science but in the policy of GM crops to address the challenges of climate change, depleting scarce natural resources and ever-increasing demand for food in view of the growing population in India. Choudhary and Mayee (2025b) elaborately dispelled the misinformation concerning CRISPR-Cas9 technology and very well highlighted that this technology, *vis-à-vis* traditional breeding and GM technology. They opined that CRISPR-Cas9 is almost analogous to genetic tailoring just like tailor using scissors to alter fabric. Genome editing, being precise, minimal and involving alteration only in own genetic material, has several benefits and potential usage (Choudhary and Mayee 2025b). The genome-editing coupled with Bt, presently only in cotton, may open new vistas in broad-spectrum insect control, management of biotic and abiotic stresses, and hybrid seed production (Choudhary and Mayee 2025c), thus yielding enhancement research. It is noteworthy that globally, transgenic soybean, corn, cotton, and canola accounted for 50.0, 32.5, 11.8, and 5.0% of the 209.8 million ha of the 2024 crop area in 27 countries, including India in 2024. India is the 5th largest country in the world, accounting for 5.3 of % area under GM crops in the world. Cotton is the only GM crop grown commercially in India, occupying about 95% of the total cotton-cropped area (Anonymous, 2025). These transgenic crops, which have insect resistance and herbicide tolerance, mitigate the challenges of insects and weeds. And no credible adverse effect of cultivating GM crops in India or worldwide has been reported during the last 25 years. Further, Jishnu (2025), while acknowledging that the development of genome-edited rice in India is a historical milestone reflecting progress in cutting-edge biotechnology, flagged an important issue of Intellectual Property Rights, as the technology used is patented. Such protected technology/ies can only be used through licensing for research purposes and product development under Trade Related Intellectual Property Rights, but invite a benefit-sharing clause for commercialization, which is a very cumbersome process involving legal issues, including fees. Even for legal licensing, engaged consultations are required among the stakeholders prior to product commercialization and preferably prior to use of such technology/ies. She also elaborated on various legal issues, even including the challenges to real ownership of this intellectual property in US courts and ICAR's efforts in addressing this issue. These are certainly the real issues that need to be appropriately resolved amicably to fast-track genome-edited rice varieties into the seed production chain so that benefits could reach the stakeholders at the earliest. About a decade back, a public sector organization dealing exclusively in plant biotechnology research was involved in controversy about Cry 1 Ac used in the development of Bt cotton, as the developer of the technology contested the claim of new Bt Cry 1 Ac by the organization. Therefore, the focus in the coming years should be on gene discovery and technology development rather than the application of borrowed technologies to avoid legal issues.

Only about 56% of the recently released varieties were inducted into the seed chain for breeder seed production during 2024-25. Therefore, there is a need to fast-track the varieties and several new crops for which many varieties have been notified, into the seed chain and develop strategies in view of the large varieties/year is being released. The variety release and notification system should also be reviewed and revamped.

Authors' contribution

All authors contributed equally.

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Conflict of interest

Authors declare no conflict of interest

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