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REVIEW ARTICLE

Recent trends in crop breeding, the varietal induction in seed chain and its impact on food grain production in India

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Abstract

Food grains in India achieved an all-time high production (310.74 mt) during 2020-21. Varietal and seed replacement rates played an important role in achieving this milestone. A total of 1646 varieties of food crops comprising 1273 of cereals and 373 of pulses were released from 2011 to 2022. Of these 977 varieties consisting of cereals (667) and pulses (310) have been inducted into the seed chain during 2020-21. New breeding technonologies such as bio-fortification of food crops and marker-assisted breeding were applied to improve crop varieties with respect to specific desirable traits. A total of 65 bio-fortified varieties comprising rice (8), wheat (28), maize (14), pearl millet (9), finger millet (3), little millet (1) and lentil (2) have been released with improved levels of proteins, essential amino acids (lysine, tryptophan), vitamins (pro-vitamin A) and micro/macro-nutrients (zinc, iron, calcium). Marker-assisted breeding adopting foreground and background selections with targeted gene(s) utilizing molecular markers such as RFLPs, SSRs, CAPs, STS and INDEL resulted in to the development and release of 66 cultivars comprising rice (43), wheat (5), maize (10), pearl millet (2) and chickpea (6) with one/and or combination of traits such as tolerance to biotic/abiotic stresses, herbicide tolerance, nutrient use efficiency, earliness, nutritional and other quality traits. These non-genetically modified crop varieties are expected to play vital role in achieving food and nutrition security in India. The paper also provides insight in to the maintenance breeding of food crops. The analysis of seed requirement and availability during 2010-11 to 2020-21 revealed that seed requirements for cereals and pulses have increased consistently by 31.6% and 62.3%, from 186.8 to 245.8 lakh q and 22.3 to 36.2 lakh q, respectively. The production of rice, wheat, maize, pearl millet and pulses during 2020-21 increased over that of 2010-11 by 27.4%, 26.0%, 45.2%, 4.4% and 41.3%, respectively. The productivity of sorghum was higher by 18.9% over that of 2010-11 but production decreased by 31.7% on account of a reduction in acreage by 42.5% during the corresponding period. The net per capita availability of food grains increased, by 17.2% from 159.5 kg to 187.0 kg during this period. The cereals and pulses production needs to be up-scaled by 5.3% and 24.4% to meet the demand by 2030 from 285.28 mt and 25.46 mt, respectively, in 2020-21, with almost the similar acreage, degrading and depleting natural resources, thus, requiring a greater focus on enhancing yield/ha. Crop-specific breeding programmes should be accelerated with the adoption of new technologies like GM, gene editing, marker-assisted selection and speed breeding to address the challenges of climate change and degrading natural sources.

Keywords: Breeding, cereals, pulses, MAS, seed production, release notification, varietal replacement rate

Introduction

Food security is very vital for peace, harmony and prosperity of any country. The Food and Agriculture Organization (FAO) defines food security as when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food, that meets their dietary needs and food preferences for an active and healthy life (FAO 2002; 2019). Challenge is likely to be magnified further with increase in population, which is expected to reach nearly 9.7 billion by 2050 (United Nations 2021). Helland and Sörbö (2014) emphasized upon availability, access and ability to purchase food to ensure sustainable food security. Bazerghi et al. (2016) viewed that threats to food security include limited supplies of nutritious and safe foods or when the consumers'

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food purchasing power is limited. Food insecurity is a serious threat to public health, social sustainability, and political stability.

The green revolution led to high productivity of cereal crops realized through increase in area, cropping intensity, use of inorganic fertilizers and pesticides, irrigation facilities, farm implements, and adoption of high yielding varieties (Singh 2000) and helped India move from a state of importing grains to a state of self-sufficiency (Brainerd and Menon 2014; Ramachandran and Kalaivani 2018). Among them, seed of high yielding varieties played major role in enhancing grain yield. However, the feat was achieved with a high investment in crop research, good infrastructure, market development, and appropriate policy support (Pingali 2012). Efforts were made to improve the genetic component of traditional crops. After the green revolution, the production of cereal crops tripled with only a 30% increase in the land area under cultivation. In addition, there were significant impacts on poverty reduction and lower food prices. Undoubtedly, the positive effects on the overall food security have been realized in India, although, after a certain period, some unintended but adverse effects of the green revolution were noticed (Eliazer 2019; Daisy et al. 2021). Still, India during the last 11 years (2010-11 to 2020-21) gained spectacular success in food production and attained an all time high 310.74 million tonnes during 2020-21 (agricoop.nic.in-web link), an increase of 26.2% over that of 2010-11. The gradual increase in food production should not make any room for complacency in view of steadily growing population likely to be 1.48 billion by 2030. The reflection in the increasing consumption of food grains due to improved standards of living will result in higher demand for food grains. To augment further production, speedy replacement of old varieties and having crop specific ideal seed replacement rate are crucial as these two factors together can result in further increase in production by up to 40%.

Development of new, high yielding and climate resilient genotypes will ever be needed for enhancing crop productivity. However, for quite some time, we have been witnessing the environmental degradation caused by increased level of CO2 and other green house gases, climatic variations incited drought and salinity conditions, increased level of pollutants and nitrogenous compounds from industrialization, rise in temperatures etc. (Porter and Semenov 2005) causing huge damages on global food production. There are growing concerns about our ability to increase crop yield and quality further or even sustain it under the changing environmental scenario. To achieve the targets of increased production of cereals and pulses, science based holistic approach is needed to adopt and execute sooner than later as the situation is already aggravated by degrading natural resources and low total factor productivity. The current situation demands the breeders to devise alternate agronomic management approaches, expanding the genetic base, adopting specific selection strategies, introgression of novel alleles, adaptation and crop modeling to improve food production, sustain yields with lower consumption of inputs including water etc. (Tester and Langridge 2010; Martin 2021).

The present paper discusses the current food grain production, breeding of varieties through conventional methods adopting wide hybridization, mutation and heterosis breeding and the latest technology of molecular breeding, recent trends of varietal release/notification and pattern of old and new varieties in seed chain during the last 11 years (2010-11 to 2020-21). Issues related to maintenance breeding, induction of new varieties in seed chain, seed availability, seed replacement and their impact on production of food grains and yield were also elaborated. Number of varieties in seed chain available for each one lakh ha of crop area was used to compare the effectiveness of breeding programmes of selected cereal and pulse crops. Similarly, to assess the effectiveness of seed chain of a crop; share of old released (> 10 years) and latest released varieties (released during 2016-20) was estimated and seed chain of a crop was termed dynamic, latent and dormant, if share of old varieties was < 25%, 26-50% and > 50%, respectively.

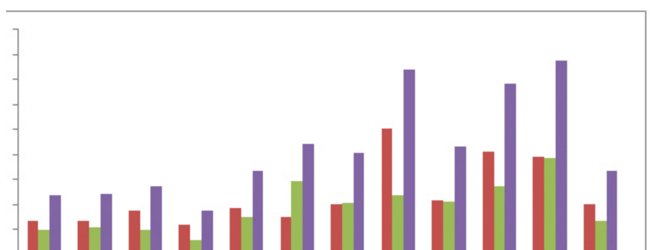
Current food grain production

During 2020-21, food grains production in India was all time high (310.74 m t) consisting of cereals (91.7%) and pulses (8.3%). Among the cereals, rice, wheat, maize, sorghum and pearl millet contributed 39.6%, 35.5%, 10.2%, 1.5% and 3.5%, respectively, to the production. Their corresponding share in acreage was 44.8%, 31.4%, 9.8%, 4.2% and 7.5%, respectively (www.agricoop.nic.in-web link). Uttar Pradesh was the leading state in rice acreage (12.6%), followed by West Bengal (12.4%), Odisha (9.0%) and Chhattisgarh (8.4%). But West Bengal followed by Uttar Pradesh and Punjab were the major states accounting together for 36.4% of the rice production (122.27 m t). Yield varied widely from 1889 kg/ha (Chhattisgarh) to 4366 kg/ha (Punjab). The overall national rice yield average was 2713 kg/ha. Major wheat producing states were Uttar Pradesh, Madhya Pradesh and Punjab sharing together 62.5% and 64.2% of the national acreage (31.61 m ha) and production (109.52 m t), respectively. Nevertheless, Punjab had the highest yield (4862 kg/ha) followed by Haryana (4836 kg/ha), Rajasthan (3676 kg/ha) and Uttar Pradesh (3604 kg/ha) as against national average of 3464 kg/ha. Karnataka, Madhya Pradesh and Maharashtra were the leading maize growing states accounted for 17.0%, 14.8% and 11.6%, respectively, of the national maize acreage (9.86 m ha). Karnataka (16.5%) was the principal contributor to the national maize production (31.51mt) followed by Madhya Pradesh (12.2%) and Maharashtra (10.9%). Tamil Nadu (6820 kg/ha) had the highest yield/ha of maize followed by Telangana (6721kg/ha) and West Bengal (6702 kg/ha), while national average was 3195 kg/ha. Sorghum was mainly grown in Maharashtra, which shared 46.1% and 36.9% of the national acreage (4.24 mha) and production (4.78 mt), respectively. Karnataka, Rajasthan and Tamil Nadu also had substantial acreage and production of sorghum. Their contribution to acreage was 17.5%, 13.4% and 9.7%, respectively and to production was 18.4% (Karnataka), 12.3% (Rajasthan) and 9.4% (Tamil Nadu). Andhra Pradesh had the highest sorghum yield/ha (3070 kg) followed by Telangana (1855 kg), Madhya Pradesh (1636 kg) and Uttar Pradesh (1578 kg) in comparison to overall average of 1128kg/ha of India. Rajasthan was the leading pearl millet growing state and contributed 57.1% and 41.7% to the national acreage (7.57 m ha) and production (10.86 m t), respectively. Seed yield/ha ranged from 425 kg in West Bengal to 2974 kg in Tamil Nadu. Further, Haryana (2372 kg), Andhra Pradesh (2303 kg), Madhya Pradesh (2256 kg), Uttar Pradesh (2221 kg), Gujarat (2192 kg) also showed considerably higher pearl millet seed yield (> 2000 kg /ha) than that of all India average of 1436kg/ha.

Of the 12 pulses grown in India, chickpea, pigeonpea, mungbean, urdbean and lentil accounted for 88.3% and 90.0% of the total pulses acreage (28.83 m ha) and production (25.72 mt), respectively, during 2020-21. Rajasthan, Madhya Pradesh and Maharashtra were the major pulses growing states contributed 21.3%, 16.9% and 15.5% to the acreage and 16.8%, 20.3% and 17.7% to production, respectively. Among the major states Madhya Pradesh (1306 kg) had the highest yield/ha followed by Uttar Pradesh (1288 kg), Rajasthan (1107 kg) and Maharashtra (1068 kg) against national average of 892kg/ha. Among the pulses, chickpea has been grown mainly in Rajasthan, Maharashtra, Madhya Pradesh and Gujarat represented 72.9% of the acreage (9.85 mha) and 75.9% of the production (11.99 mt) of this crop. Seed yield/ha was highest in Gujarat (1568kg) followed by Madhya Pradesh (1488 kg), Maharashtra (1105 kg) and Rajasthan (1099 kg). Overall, it ranged from 695 kg (Assam) to 1671 kg (Telangana) with national average of 1217 kg/ha. Karnatka and Maharashtra were the leading states for pigeonpea cultivation and accounted for 34.0% and 25.7% of the cropped area (4.80 mha) and 28.9% and 29.9% of the production (4.28 mt), respectively. Seed yield varied widely across the country and ranged from 357 kg/ha in Andhra Pradesh to 1647 kg/ha in Kerala and overall yield was 892 kg/ha in India. Rajasthan is the principal mungbean growing state contributing 49.5% and 45.5% to its acreage (5.15 mha) and production (3.09 mt), respectively, with seed yield of 551 kg/ha. Madhya Pradesh, Karnataka and Maharashtra were the other major mungbean growing states with share of 10.6%, 8.8% and 8.3% to acreage and 19.7%, 5.9% and 7.3% to the production, respectively. Seed yield/ha ranged from 292 kg (Odisha) to 1110 kg (Madhya Pradesh) and all India average was 599 kg/ha. Urdbean was mainly grown in Madhya Pradesh, Uttar Pradesh, Rajasthan, Tamil Nadu and Maharashtra, each contributed 31.7%, 13.1%, 9.8%, 9.6% and 9.3%, respectively, to the all India acreage (4.21 mha). However, Madhya Pradesh (21.5%) followed by Andhra Pradesh (15.3%), Uttar Pradesh (13.4%) and Maharashtra (11.0%) were the principal states accounted for 61.2% of the production (2.34 mt). Seed yield/ha varied from 349 kg (Rajasthan) to 1274 kg (Telangana) against the national average of 557 kg. Lentil was mainly grown in Madhya Pradesh followed by Uttar Pradesh with a share of 31.4% and 28.5%, respectively, in crop acreage (1.45 mha) and 40.9% and 32.2% in production (1.45 mt). West Bengal and Bihar were the other major lentil growing states with share of 11.0% and 9.2% in acreage and 9.4% and 8.0% in production, respectively. Seed yield/ha ranged from 404 kg in Chhattisgarh to 1390 kg in Rajasthan, while among major states; it was 1139 kg in Madhya Pradesh, 988 kg in Uttar Pradesh, 855 kg in West Bengal and 868 kg in Bihar whereas; all India average was 1001 kg.

Breeding of food crops

India has a strong well-organized crop improvement programme under crop specific All India Coordinated Research Project (AICRP) and All India Net Work Project (AINP) under ICAR, New Delhi since late 1950's. Chauhan et al. (2016a) discussed in details the genesis of various AICRPs, the mandate, organizational structure and network of testing. Technological assessment through conduct of front line demonstrations and production of breeder seed are the two important mandated activities of AICRPs besides testing and identification of candidate varieties. They serve as important sources for Indian seed systems by channeling newly developed varieties in to seed production chain (Chauhan et al. 2016a). The sustained and dynamic crop specific varietal improvement programme led to release and notification of 6113 input-responsive, high yielding, tolerant against major diseases and insect pests, climate resilient (drought, heat, cold and salinity tolerant) and suitable for conservation agriculture, varieties of all the field crops since the first



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
al	67	68	87	59	92	75	101	253	109	205	195	99
	50	53	50	29	74	147	103	118	106	137	194	67
	117	121	137	88	166	222	204	371	215	342	389	166

Fig. 1. Trends in release and notification of varieties and hybrids of field crops during 2011-2022

meeting in 1969 till 88th meeting of Central Sub-Committee on Crop Standards, Notification and Release of Varieties for Agricultural Crops on June 17, 2022 (https://seednet.gov.in-weblink). About 41.5% (2538) comprising 1403 and 1135 varieties for central (more than one state) and state (single) respectively, were released and notified during 2011-2022 (Fig. 1.) and Number of varieties released per year ranged from 88 (2014) to 389 (2021). And, all these varieties qualify for seed and commercial production as per Seeds Act 1966.

Currently, nine AICRPs, one NNRP and one National Seed Project rechristened during 2021, as AICRP on Seed, spread all over crop specific agro-climatic zones of the country, exclusively deal with crop improvement and seed production research of food crops (www.icar.org.in-weblink). Of the 2538 varieties of field crops released and notified during 2011-22, 1646 belonged to food crops comprising 1273 of cereals and 373 of pulses. Among the food crops the highest number of varieties released was for rice followed by maize, wheat and chickpea (Table 1.). Further, during this period, special efforts were initiated for bio-fortification of varieties, considering the most sustainable and cost-effective approach to alleviate malnutrition. A total of 79 varieties/hybrids of 11 field crops were bio-fortified for 13 traits. Such varieties have improved levels of proteins, essential amino acids (lysine, tryptophan), vitamins (pro-vitamin A) and micro-macro-nutrients (zinc, iron, calcium) as well as free from anti-nutritional factors like erucic acid, glucosinolates, Kunitz trypsin inhibitor and lipoxygenase. Among the food crops, a total of 65 bio-fortified varieties comprising rice (8), wheat (28), maize (14), pearl millet (9), finger millet (3), little millet (1) and lentil (2) have been released and notified until 2021 (Yadava et al. 2022a).

Breeding methods used

The breeding methods used in self-pollinated crops are employed in breeding of rice, wheat, barley, finger millets and most of the pulses (except pigeonpea) and clusterbean. They include selection, pedigree, back crossing and mutagenesis. The major focus is to develop pure line varieties. In cross pollinated crops like maize, pearl millet and sorghum breeding methods such as mass selection, modified mass selection, ear-to-row selection, recurrent selection, development of composites/synthetics, back crossing and mutagenesis are used with a view to develop open pollinated varieties, composites and synthetics. Besides these, heterosis breeding is also pursued in pigeonpea and rice. The targeted traits, in general, in all the crops are yield and yield contributing characters although crop specific

Table 1. Varieties of food crops released during 2011-2022*

Crop	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
Cereals													
Rice	29	23	39	22	45	41	61	93	43	61	81	53	591
Wheat	15	8	11	13	16	16	14	27	15	16	21	5	177
Maize	11	19	16	11	18	14	24	25	15	24	24	14	215
Sorghum	2	5	8	2	4	8	1	15	7	5	10	4	71
Pearl millet	10	12	5	3	5	15	3	15	6	6	8	5	93
Barley, small millets, grain amaranth, etc.	6	7	5	10	5	11	11	23	9	21	14	4	126
Total	73	74	84	61	93	105	114	198	95	133	158	85	1273
Pulses													
Chickpea	1	5	5	1	5	8	10	4	17	17	20	1	94
Pigeonpea	2	2	3	2	1	5	2	8	7	12	15	0	59
Mungbean	3	3	1	3	3	9	3	8	3	5	4	5	50
Urdbean	4	4	3	1	2	2	1	7	10	6	8	2	50
Lentil	2	1	1	1	1	2	6	5	8	6	3	1	37
Fieldpea	3	2	0	2	3	4	2	5	2	4	3	0	30
Cowpea, arid legumes and others	2	1	1	2	3	3	8	10	4	0	19	0	53
Total	17	18	14	12	18	33	32	47	51	50	72	9	373
Grand Total	90	92	98	73	111	138	146	245	146	183	230	94	1646

* 88th meeting of Central Sub-Committee on Crop Standards, Notification and Release of Varieties for Agricultural Crops on June 17, 2022.

traits such as effective tillers, panicle/cob length, spikelets/panicle, no. of grains/cob or/ear head, 1000-grain weight and harvest index have been common for the improvement of cereals. Similarly, number of pods/plant and no. of seeds/pod and 100-grain weight are given due weight-age in pulses. To reduce the widening gap between potential and realized yields, tolerance/resistance traits that provide protection against yield losses caused by biotic (weeds, diseases and insect pests) and abiotic (secondary/micro nutrient deficiency and toxicity, temperature extremities, drought, salinity, water logging, submergence and flooding) are the other traits of interest in breeding these crops. Further, crop specific quality traits including both, physical like grain length, shape (rice), grain texture (maize, pearl millet, sorghum, mungbean) and chemical quality traits such as protein, minerals (rice, wheat, barley and finger millets); and essential amino acids, provitamin A (maize), amylose content, gelatinization temperature, aroma, kernel linear elongation and cooking quality in rice, bread making quality in sorghum and wheat, brewing quality in barley are some of the illustrative target quality traits of interest in breeding of the food crops. Breeding for quality traits coupled with yield offers excellent opportunity for increase farmers' income and alleviating malnutrition testing for identification of desired genotypes.

In all the crops, in general, the breeding is initiated with the selection, identification of useful genes from the germplasm, their deployment for genetic enhancement through hybridization to develop single/double/multiple crosses, handling of segregating generation, selection for the target trait(s) and multi-location testing for identification of desired genotypes. The scheme of hybridization depends on the mode of reproduction of the crop.

Cereals

Pure line selections and pedigree selections are the earliest methods of rice (*Oriza sativa* L.) breeding and pure line selection led to the development and notification of 445 varieties across India. Of these 54 were developed during the last two decades of 20th century for irrigated (19) and rainfed (35) ecosystems (Patra et al. 2020).

Some of the recently developed and released varieties in 2016 through pure line selection are Badshabhog Selection 1, Tarunbhog Selection 1, Dubraj Selection 1 and Vishnubhog Selection 1 from Chhatitsgarh. Recombinant breeding in rice in India started with *indica* x *japonica* hybridization and first high yielding variety ADT 27 was identified and released. Another resultant variety of this programme was Mahsuri which became quite popular throughout India and many other countries. Two mega varieties of India, Swarna and BPT 5204 have Mahsuri as one of the common parents. Recombination breeding encompasses different breeding methods such as pedigree breeding, population improvement and hybrid breeding based on the objectives and target traits (Patra et al. 2020). Almost all the varieties released in India post 1960s are derived from pedigree breeding. CR 312, a rice variety was developed through population improvement using genetic male sterile IR 36 for recurrent selection utilizing more than 10 diverse parents and released during 2019 (Patra et al. 2020).

In rice, hybrid rice technology project was launched during 1989 under the project, Promotion of Research and Development Efforts on Hybrids in selected Crops. The first hybrid, APRH 1 was released in 1994 and till 2021, a total of 127 hybrids have been released (Chakraborti et al. 2021) from both the public and the private institution. Hybrids have been developed for various ecologies including those prone to various abiotic stresses as well as specific consumer needs. Some suitable hybrids for different agro-ecological niches are PSD 3, Rajlaxmi, Ajay, KRH2, DRRH 44 and JK RH 3333 (aerobic conditions); CRHR 105, PNPH 24, Arize Tej, US 382 and US 312 (early duration); CRHR 32, Sahyadari 5 and CRHR 100 (long duration); KRH 4 and TNRH CO 4 (SRI); VNR 2335+ (idly making); 27P63, CRHR 32 and DRRH 3 (MS grains) and PRH 10 and PRH 122 (aromatic). Hybrid development in rice utilized both CMS-based three-line system as well as EGMS-based two-line system. PUSA RH 10, DRRH 2, KRH 4, Rajlaxmi, Ajay, CR Dhan 701 and TNRH 24 are some of the leading hybrids from public sector institutions (Patra et al. 2020). Mutagenesis is another potent method of developing high yielding varieties and many mutant varieties, namely, Vikram Trombay Chhattisgarh Rice, Chhattisgarh Jawaphool Trombay, Trombay Chhattisgarh Sonagathi Mutant, Trombay Chhattisgarh Vishnubhog Mutant and Trombay Chhattisgarh Dubraj Mutant 1 were released during 2018-21.

Yield enhancement has been the major objective of wheat breeding in India. However, traits of interest to consumers and grain characteristics are also emphasized. Subsequent to the establishment of AICWIP during 1965, the intensive hybridization involving dwarf genotypes resulted in to the development of several high yielding wheat varieties possessing disease resistance (Gupta et al. 2018). Indian wheat programme caters to the need of diverse production niches such as rainfed early sown; rainfed timely sown; rainfed/irrigated, timely sown; restricted irrigation, late sown; irrigated, timely and/or late sown, restricted irrigation, timely sown; restricted irrigation, late sown and rainfed/restricted irrigation, timely sown of the six zones as well as across the zones. Gupta et al. (2018) presented a detailed account of pedigree, breeding methods and suitability to different agro-ecological conditions of 448 varieties of wheat comprising bread (*T. aestivum*), durum (*T. durum*), *T. dicoccum* and triticale. Almost all the varieties post 1965 were developed by recombinant breeding, nevertheless, among the varieties released during 2011-22, WH 1080, PDKV Wasim (WSM1472), PDKV Sardar (AKAW

4210-6) and NIDW 15 (Panchavati) were developed through selection and Nilgiri Khapli and CoW 2 (HW 1095) were the mutant varieties. Most of the wheat varieties have been developed either through introduction or hybridization and selection. Direct use of wheat species for developing cultivars is done at very limited scale.

However, work on pre-breeding utilizing related and distantly related wheat species adopting special techniques of recombination is being carried out for incorporating disease resistance and other useful desirable traits for improvement in wheat (Tomar and Vari 1990; Sharma and Singh 2000; Durgesh et al. 2011; Rani et al. 2020; Dhillon et al. 2021; Niranjana et al. 2017). A bread wheat variety HD2888 derived from *T. aestivum* cv. C306/*T. sphaerococcum*// HW2004 has been released for rainfed conditions (Singh et al. 2007), whereas one each of *Triticum durum* and *T. dicocccum* (tetraploids) varieties, JNK-4W-184 (Jairaj) derived from a cross between *T. polonicum* and *T. durum* and DDK1001 is a derivative of *T. dicoccum*/*T. durum* cv. Raj 1555, respectively have been released (Gupta et al. 2018).

In maize (*Zea mays* L.), enhancement in productivity and production to meet the increasing demand of human food, animal feed and industry for starch, oils and other value added products, are the major objectives of crop improvement programme. Until the first decade of 21st century, 234 varieties (mostly composites) and 132 hybrids of field corn, quality protein, baby corn, sweet corn, pop corn and fodder have been released since 1961 (Kaul et al. 2010). Further, more than 200 hybrids were released during 2011-22. Yadav et al. (2015) reported that development and evaluation of multi-parent hybrids of maize was initiated after the establishment of AICMIP in 1957 although first indigenous hybrid, Punjab Hybrid 1, was released during 1956. Four double cross hybrids (Ganga 1, Ganga 101, Ranjit and Decan) were released in 1961. The focus of maize improvement programme was development of composites in addition to multi-parent hybrid breeding during 1970-88, when more than 50 composites were released as compared to 10 double-and double-top cross hybrids. Since early 1980s, the hybrid development was reemphasized and focus shifted to single cross hybrids (SCH) and more than 80 SCHs were released (Yadav et al 2015). Some of the important hybrids are DHM 117, Sheetal, Vivek Hybrid 21, PMH 1 and Vivek Hybrid 43 from public sector and Bio 9681, M Gold, DKC 9108, PAC 740 and PAC 750 from private sector. Jawahar Maize 218, MAH 14-5, Shalimar Pop Corn 1 (KDPC-2), Vivek Sankul Makka 35 (VL 113) and Birsa Vikas Makka 2 are some of the important OPVs/composites and Pusa HQPM-7 Improved (APQH7), IMHQPM 1510, Pusa HQPM-5, Vivek Hybrid Maize 57 and DMRH-1308 and recently released hybrids in the seed production chain.

Breeding strategies in pearl millet (*Pennisetum glaucum* L.) have evolved over a period of many decades considering its pollination behavior, challenges in its production, access to germplasm and emerging frontiers in research (Yadav et al. 2021). Because of its highly cross-pollinated nature, the individual plants of natural populations are highly heterozygous and heterogeneous. This existing genetic variability within the traditional land races was successfully utilized by simple mass selection/progeny selection and many varieties were developed (Table 2). During the last 40 years, hybrid breeding has received very high priority in India, using diverse parental lines targeting various production agro-ecologies (Yadav et al. 2012). The major target traits in hybrid breeding besides grain yield, are tolerance to abiotic (drought and heat), biotic stresses (downy mildew, blast, rust, smut and ergot and insect pests) and grain nutrition (Fe and Zn content). The National Agricultural Reserch System in India and ICRISAT have played a pivotal role in pearl millet breeding by developing diverse range of improved breeding lines and parental lines, proved to be invaluable resources for the development of varieties and hybrids. One hundred-sixty-seven hybrids and 61 varieties were released and notified through the ICAR-All India Coordinated Research Project on Pearl Millet (Tara et al. 2018). However, X1 was the first hybrid released during 1950 from the cross PT 348 x PT 350 and HB 2 was the first hybrid notified in 1969. MP 535 (Pusa Composite 701), Peal millet CO 10 and Mandore Bajra Copmosite 2 are some of the recently released composites/OPVs. And, HHB 311, RHB 234, AHB 1269, ICMA 98222F, HHB 299 and AUB 1105 are the recently released hybrids in the seed production chain.

Sorghum (*Sorghum bicolor* L.) in India is grown in both rainy (*kharif*) and post rainy (*rabi*) season and has diversified usages such as food and fodder. In crop improvement programme, the objective is on the development of varieties as well as hybrids grain and/or fodder suitable for rainy and post-rainy season. Many important varieties were the result of selection, M 35-1 is still very popular and in the seed chain. Hybridization followed by pedigree selection and mutagenesis also led to the development of a good number of varieties (Table 2). With the discovery of cytoplasmic-nuclear male sterility, Kafir-60 (ms CK 60, milo cytoplasm) and initiation of the accelerated sorghum project in 1962, hybrid breeding was emphasized. During 1962-69, hybrids CSH 1, CSH 2 and CSH 3 were released from temperate X temperate and temperate X tropical crosses using germplasm from the USA, Kafir milo cytoplasm and other germplasms (Elangovan et al. 2012). Since then, several important hybrids were released in India for *kharif* (CSH 22 SS, CSH 18, CSH 17, CSH MF 24, CSH 25, CSH 23 and CSH 20 MF) and *rabi* (CSH 19R, CSH 15 R, CSH 12 R and CSH 8R) seasons. Some of the recently released varieties (2016-20) in the seed chain are PDKV Hudra Kratiki (WAN-103), CSV-37 (SPV-2366), BJV-44 (SPV 2034), CSV 41, CSV 34 (SPV-2307), Raj Vijay Jowar 1862 and Phule Vasundhara. Hybrids CSH 35 and CSH 39 released in 2016 and 2019, respectively, were also in the seed chain. Two mutant varieties, *viz*., CO 31 and CS33MF of sorghum were also released during 2014 and 2016, respectively.

Pulses

Pulses are among the important food crops globally due to higher protein content and other nutritional components. In India also pulses forms an important group of crops not only from the nutritional point of view but due to large financial gains. Several varieties of the pulses in India were developed by selection from the indigenous as well as exotic cultivars, introduced through NBPGR, New Delhi. The desirable plants were selected and after their progeny testing the superior pure lines were established. The pure lines were evaluated for yield, yield traits and for reaction to diseases and the best pure line was released for cultivation. But during 2011-22, recombinant breeding involving one adapted cultivar of the area/region and the other parent as the donor for specific trait(s) of interest like biotic or abiotic stress or quality and/or yield trait has been predominantly used for developing superior varieties of pulse crops. In general, intra-specific hybridization has been used and rarely inter-specific hybridization has been used for genetic enhancement. Largely, single crosses have been attempted and the segregating generations were handled using pedigree method or its modifications. Varieties released during 2011-20 and appearing in the topmost list, five varieties indented for breeder seed production in the seed chain are presented in Table 2.

In India the wild species and their relative species have been used for the genetic enhancement of pulse crops by creating new genetic combinations. The wide crosses were made to bring in genetic improvement on the limited scale to create transgressive variations, develop CMS system and transfering the gene(s) for biotic and abiotic stresses. The CMS systems have been developed by integrating the cytoplasm of wild species with the genomes of cultivars of pigeonpea through inter-specific hybridization followed by selection and back crossing (Saxena et al. 2010). Inter-specific crosses were made between mungbean (*Vigna radiata*) and blackgram (*V. mungo*) to improve both the species simultaneously. In general, the success has been achieved when black gram was used as male parent. Six varieties of mungbean were developed from inter-specific hybridization and Pant Mung 4 being the first variety released during 1997. Further, two varieties of blackgram, Vamban 7 and TU 40 were also released during 2011. The programme on utilization of wild species of *Cicer* was initiated at IARI, New Delhi to improve chickpea for higher productivity (Yadav et al. 2002). Pusa 1103 is the first chickpea variety developed through interspecific hybridization utilizing wild species, *Cicer reticulatum* released in 2005 for the National Capital Region of Delhi (Yadav et al. 2007). It is medium bold seeded variety, suitable for late planting, yielding 20-24 q/ha. It possesses resistance against wilt, root rot, and bruchids. Recently, a new variety of chickpea (*Cicer arietinum* L.) PBG8 derived from an interspecific cross, *Cicer arietinum* x *C. judaicum* developed by Singh et al. (2022) has also been released in 2021. It is a first variety developed in the

Table 2. Trends of varietal replacement in selected cereals and pulses and contribution of varieties released during 2011-2020

Crop	Topmost five varieties with contribution (%)	Total contribution to breeders' seed indent (%)
Cereals		
Rice	Pusa Basmati 1509 (3.1%)	59.0
Wheat	Pusa Gautami (10.0%), HD 2967 (9.7%), Karan Vandana (9.5%), Pusa Yashasvi (6.7%), Pusa Tejas (5.0%)	83.8
Maize	Pratap hybrid maize 3 (14.6%), Jawahar maize 218 (12.2%), DHM 121 (9.7%), Shalimar pop corn (8.1%)	61.0
Pearl millet	Dhanshakti (43.5%), ABPC 4-3 (10.8%), Pusa composite 612 (8.4%), MPMH 21 (8.4%), MPMH 17 (6.4%)	80.0
Sorghum	CSH 24 (10.1%), Phule Revati (3.4%), PSV 56 (2.2%)	12.6
Pulses		
Mungbean	IPM 205-7 (25.4%), IPM 2-14 (15.6%), IPM 410-3 (15.1%), IPM 421 (8.4%), RMG 975 (6.8%)	87.8
Blackgram	Indira Urd 1 (12.2%), LBG 787 (11.6%), Lam Minimu (10.9%), Pratap Urd 1 (8.6%)	61.3
Pigeonpea	IPA 203 (14.7%), BDN 716 (14.4%), Rajiv Lochan (10.9%), Phule 12 (8.2%)	66.7%
Chickpea	Raj Vijay Gram 202 (9.3%), Meera–GNG 2171 (8.6%), GNG 2144 (8.0%), Raj Vijay Gram 203 (5.0%)	80.0%
Lentil	L 1417(10.9%), KLS 9-3 (9.4%), IPL 316 (7.8%), Shekhar 5 (7.0%), IPL 220 (6.9%)	90.8
Fieldpea	Central field pea-IPFD 12-2 (14.7%), Dantiwada field pea 1 (14.7%), Punjab 89 (7.6%), IPFD 9-2 (7.4%), Central field pea-IPFD 11-5 (6.9%)	85.3

world through conventional method breeding utilizing *C. judaicum*.

Exploitation of heterosis

Presence of considerable non-additive variation for yield components have raised the prospects for exploitation of hybrid vigour in pigeonpea, an often cross-pollinated crop with out-crossing to the extent of 20% mediated by insects mostly bees. Therefore, during 1980's sincere efforts were made to develop pigeionpea hybrids using genetic male sterility (GMS). Using GMS, five pigeonpea hybrids (ICPH 8, PPH4, CoPH-1, CoPH 4, and AKPH 4101) were developed and released in India, the first being, ICPH 8, released during 1991.

Mutation breeding

Induced mutations have been found useful in creating variability for yield traits, plant type and resistance to various stresses. In general, gamma-irradiation has been used for mutagenesis and seldom chemical mutogens have also been used. A large number of varieties of different pulse crops with improved plant type, seed size, seed colour, maturity duration and resistance to disease(s) have been developed through mutation breeding (Table 3). A total of 52 mutant varieties of different pulse crops comprising of chickpea (15), pigeonpea (5), mungbean (12), blackhram (7), pea (1), lentil (2), mothbean (6), cowpea (3) and horsegram (1) were released until 2013. [Singh D. P. and Singh B. B. Hundred years of pulse research in India, unpublished data; Solanki et al. (2011)]. However, during 2011-22, not much emphasis was laid on mutagenesis for pulse improvement.

Marker-assisted breeding

Traditionally, the development of a new cultivar use to take a long period of about 10 years. Here, the phenotypic selections are based on field screening considering genotype and environmental interactions throughout the breeding cycles. Molecular breeding has now become very common in research institutions to develop new cultivars or to convert popular cultivars deficient in agronomic/quality trait(s) with desired gene(s). Marker-assisted breeding adopting foreground and background selections take lesser time than conventional breeding methods for developing crop varieties with targeted gene(s) utilizing molecular markers (SSRs, CAPs, STS, INDEL and RFLP), whole genome sequences and linkage maps in many crops and tagging/mapping of a number of gene(s)/QTL(s) governing various traits for biotic and abiotic stress tolerance/resistance and quality improvement (Gupta 1 et al. 2012). The molecular breeding is being vigorously practiced in Indian research institutions and so far 74 varieties of field seven crops have been released during the last decade.

Cereals

Rice (*Oryza sativa* L.) is one of the major crops of India and is produced in almost all the states. India is the world's second-largest producer of rice and the largest exporter of rice in the world. It is also the second most-consumed grain in the world, after wheat, and constitutes the dietary stable of half of the world population. The crop is attacked by several diseases such as bacterial leaf blight, blast and abiotic stresses like floods, drought and salinity etc. thereby reducing yield and affecting production. After studying the effectiveness of bacterial blight (BB) resistance gene(s) and gene combinations against the prevailing isolates of *Xanthomonas oryzae* pv. *oryzae*, the marker assisted improvement of the popular rice varieties, which were highly susceptible to BB was initiated at different centers in the country (Singh et al. 2019). Several gene-pyramided lines were developed through backcross breeding, with integration of selecting genes conferring resistance to BB applying foreground selection. For the recovery of recurrent parent genome the background selection was used (Singh et al. 2001). Popular *indica* rice cultivar, PR106 and others were used initially for the improvement of BB resistance, leading to the commercial release of Improved Pusa Basmati 1 (*xa13*, *Xa21*) and Samba Mahsuri through MAS having *Xa21*, *xa13* and *xa5* genes, respectively (Gopalakrishnan et al. 2008; Sundaram et al. 2008) retaining both yield and quality. Improved Pusa Basmati 1 was the first rice variety in India developed in 2007 through marker assisted backcross breeding (MABB) integrating genes for bacterial leaf blight (BLB) resistance using CAPS and STS markers into the genetic background of rice cultivar, Pusa Basmati 1. A series of rice varieties namely, Improved Lalat (*Xa4*), Akshay Dhan (*Xa33*) and DRR Dhan 53 (*Xa21*, *xa13*, *Xa38*) etc. possessing different genes and their combinations for BB were developed and released for commercial cultivation. Pusa 44, a popular variety grown commercially in Punjab was introgressed with BB resistance gene *Xa 45*(t) from *Oryza glaberrima*.

Concurrently, other rice varieties were also developed for blast resistance, sub-mergence tolerance, salinity, drought and low phosphorus tolerance combining BB resistance genes. A major QTL – *Sub1* was transferred into mega rice cultivar, Swarna, through MABB for improving flood tolerance (Neeraja et al. 2007), resulting in the development of a flood tolerant cultivar, Swarna – *Sub1*. The total cumulative production of this new variety was about 7 lakh tonnes during 2011-16 with an average yield of 5.7 t/ha (Reddy 2017). The efforts to develop improved varieties are continued to evolve new varieties with specific genes, namely, Improved Swarna (*qSub1*), Pusa 1612 (*Pi2* and *Pi54*), Pusa 1637 (*Pi9*), Pusa 1850 (*Pi1*, *Pi54*, *Pita*), DRR Dhan 62 (*Xa21, xa13, xa5, Pi2* and *Pi54*), DRR Dhan 58 (*Xa21, xa13, xa5* and *qSaltol*), DRR Dhan 50 (*qSub1, qDTY2.1, DTY3.1*), CR Dhan 801 (*qSub1, DTY1.1, DTY2.1, DTY3.1*) and IR64 Drt 1/DRR

Table 3. Breeder and foundation seed production, certified/quality seed distribution and seed replacement rate of selected crops

Crop	Breeder seed (q)				Foundation seed (lakh q)				Certified/quality seed distributed (lakh q)			Seed replacement rate (%)		
	2019-20		2020-21		2019-20		2020-21		2018-19	2019-20	2020-21	2018-19	2019-20	2020-21
	[I]	[P]	[I]	[P]	[R]	[A]	[R]	[A]						
Cereals														
Rice	9884	19120	8442	19651	1.90	4.54	3.80	6.83	72.40	84.63	91.69	33.1	37.9	41.5
Wheat	29457	49301	31388	51057	4.65	10.14	5.43	10.11	118.04	126.84	134.96	39.6	41.5	42.5
Maize	90	355	126	224	0.054	0.051	0.036	0.033	11.16	12.72	13.71	68.8	67.6	82.9
Sorghum	65	260	72	122	0.014	0.024	0.014	0.02	1.42	1.88	1.58	27.9	34.3	36.4
Pearl millet	9	67	7	14	0.001	0.002	0.001	0.012	1.91	2.06	2.05	58.2	36.0	54.0
Barley/ others	660	1145	692	1408	0.109	0.16	0.10	0.10	1.93	1.80	2.01	25.6/54.2	25.2/52.2	27.1/53.3
Total	40163	70247	40752	72485	6.71	14.91	9.38	17.11	206.87	229.98	246.00	NA	NA	NA
Pulses														
Chickpea	11687	13292	11396	12972	1.23	1.62	1.47	1.48	19.50	22.46	20.87	34.8	30.9	26.7
Pigeonpea	303	954	376	513	0.079	0.14	0.01	0.187	2.42	2.58	2.63	51.5	61.1	55.8
Mungbean	808	936	736	873	0.052	0.16	0.063	0.13	2.20	2.37	2.35	28.7	36.4	32.3
Urdbean	808	529	817	748	0.074	0.18	0.073	0.14	2.23	2.18	2.41	30.8	32.6	38.5
Lentil	808	1037	813	1037	0.060	0.11	0.083	0.11	1.27	1.45	1.63	30.7	40.5	44.7
Field pea	846	1058	846	1058	0.19	0.26	0.21	0.19	2.77	1.79	1.54	37.5	32.1	32.2
Cowpea/others	430	373	463	390	0.029	0.061	0.0.45	0.085	1.40	1.34	1.26	NA*	NA	NA
Total	15285	18179	15448	17590	1.71	2.52	2.033	2.31	31.80	34.16	32.70			

NA = Not available; [I] = Indent; [P] = Production; [R] = Requirement; [A] = Available.

Dhan 42 (*qDTY2.2, DTY4.1*). Recently, DRR Dhan 60 (Improved Samba Mahsuri) has been released having resistance to BB and tolerance to low phosphorus condition carrying the genes, *Xa21, xa13, xa5* and *Pup1* (Swamy et al. 2020). Since then (2007) about 42 rice varieties, through MAS and MABB using molecular markers, have been developed carrying different genes and their combination characterising various agronomic and disease resistance genes (Yadav et al. 2022).

Wheat is another important cereal crop consumed across the world after rice. Similar to rice crop, wheat is also attacked by several diseases, prominently the wheat rusts (*Puccinia* spp.) and abiotic stresses like heat, salinity and drought. Frequently, rusts cause epidemics and damage the crop. In wheat, stripe rust resistance was introgressed through marker assisted selection (MAS) using CAPS and SSR markers. Initially, wheat variety PBW 550 was improved with stripe rust resistance introgressing *Yr15* gene using SSR markers, which resulted into PBW 761 for timely sown conditions and PBW 757 released for late sown conditions. PBW 621 was also improved for stripe rust resistance transferring *Yr10* gene from which originated improved variety, PBW 752. Later on, PBW343 was introgressed with *Aegilops umbellulata*-derived genes, *Yr40* and *Yr57* and *Aegilops ventricosa*-derived linked genes *Yr17, Lr37, Sr38*. This led to the development of Improved varieties PBW 723 (*Yr17, Yr40, Lr57*) and PBW 771 (*Yr40* and *Lr57*) using marker assisted backcross breeding (Yadav et al. 2022). Very recently, two varieties namely, Unnat HD 2967 and Unnat HD 2932 have been identified for release. Both these varieties developed via wide hybridization using backcrossing and MABB carry a leaf rust resistance gene *LrTrk* from *Triticum turgidum* var. *durum* cv. Trinakria (Mallick 2022ab). Interestingly, the mega variety HD2967 has been identified to carry linked genes *Lr37, Lr38, Yr17* (2NS/2AL translocation) from *Aegilops ventricosa* (Agarwal et al. 2021).

Maize is widely grown throughout the world and has the highest production of all the cereals. In India, it is the third most important cereal crop being consumed in various forms as grain, as cob, popped, animal feed and having many industrial applications. Beside the grain and fodder yield the quality of grain is very important aspect of research. A MAS-derived hybrid, Vivek QPM9, was developed in 2008 having improved lysine and threonine content by introgressing *opaque-2* allele (Gupta et al. 2013). Introgression of *opaque 2* was carried out using marker assisted selection (SRR markers), three hybrids namely, Pusa HM 4 Improved, Pusa HM 8 Improved and Pusa HM 9 Improved with exceeded level of lysine and tryptophan (amino acid) content were release in 2017 (Hossain et al. 2019). Concomitantly, two hybrids, *viz*., Pusa Vivek QPM 9 Improved and Pusa Vivek Hybrid 27 were introgressed with *crtRB1* gene enhancing the level of provitamin A. Both these hybrids were released in 2017 and 2020, respectively. At the same time, two hybrids, Pusa HQPM 5 Improved and Pusa HQPM 7 Improved were developed with a combination of *crtRB1* and *lcyE* genes through MAS using InDel markers for enhanced level of provitamin A. These two varieties were also released in 2020 (Hossain et al. 2022a,b). Further, Pusa HQPM 1 Improved and Pusa Biofortified Maize Hybrid 1 with introgression of both the genes *crtRB1* and *lcyE* with higher contents of Provitamin A were developed and released in 2021 (Hossain et al. 2022ab). Keeping the pace of genetic improvement through marker assisted breeding, the Indian Institute of Maize Research released the first low phytic acid maize hybrid PMH 1-LP, an improved version of PMH-1, a yellow maize hybrid released by the PAU, Ludhiana in 2007, through marker assisted selection (SRR markers) for a naturally occurring mutation (www.google.com.article/cities/ludhiana-webink). This hybrid has 36% lower phytic acid than the original version. Two maize hybrids *viz*., APH 2 and APH 3, rich in provtamin A, lysine and tryptophan amino acids through introgressing of *crtRB1* gene using MABB developed by IARI, New Delhi; VLQPM Hybrid 45 and VLQPM Hybrid 61 with improved levels of tryptophan and lysine from VPKAS, Almora have been released in August 2022 (https://seednet.gov.in-weblink).

In pearl millet, a MAS-derived hybrid, Improved HHB 67, resistant to downy mildew conferred by genes, *qRSg1* and *qRSg4* introgressed through using RFLP markers, has been released in India during 2005 (https://www.millets.res.in). By introgressing three downy mildew resistance loci/QTLs (*qRSg3, qRSg4.2* and *qRSg6.1*) tagged with SSR markers led to the development of HHB 67 Improved 2 hybrid. Further, in rice and wheat, the molecular markers are being developed for Fe/Zn bio-fortification.

Pulses

Pulses form an important group of crops in India. Most of the breeding work has been done through hybridization and selection. Due to some important factors, molecular assisted breeding has not been followed vigorously in pulses. Recently, translational genomics have played a significant role and paid rich dividends in chickpea improvement. In this endeavour a popular chickpea variety Annigeri-1, susceptible to *Fusarium* wilt, has been improved by introgressing a genomic region (resistance gene *foc4*) conferring resistance against race 4 of *Fusarium*, and a first wilt resistant variety Super Annigeri 1 has been developed through MAS (Mannur et al. 2019). Introgression of QTL Hotspot for drought tolerance has led to the development of Pusa Chickpea 10216 through MAS (Bharadwaj et al. 2021). Simultaneously, IPCL 4-14 in the background of DCP92-3 and Pusa Chickpea 4005 in the background of Pusa 362 have been released for drought conditions carrying QTl Hot spot region on LG4. Similarly, a mega *desi* chickpea variety Pusa 391, susceptible to *Fusarium* wilt has been improved through marker assisted breeding incorporating wilt resistance genes, *foc1, foc2, foc3, foc4* and *foc5* using three SSR markers (*GA16, TA 27* and *TA 96*) has been released for general cultivation (Bhardwaj et al. 2022). At the same time IPCMB 19-3 (Samiridhi) with introgression of *foc2* gene in the background of Pusa 256 has been developed through molecular assisted backcross breeding (MABB) using SSR markers.

The country has achieved some important milestone in crop improvement through marker assisted breeding. In this effort, a total of 74 cultivars in seven crops have been developed for 20 improved traits such as, tolerance of biotic/abiotic stresses, herbicide tolerance, nutrient use efficiency, earliness, nutritional quality and other quality traits, including the Kunitz tripsin inhibitor (KTi3) in soybean, beany flavour and resistance to Yellow Mosaic Virus and; groundnut for high oleic acid contents by molecular breeding till recently in India (Yadava et al. 2022b)

Genome editing

Genome editing (CGE) technology refers to edit or modify the organism's native genome through deletion/insertion or substitution of certain nucleotides or a full-length gene at a specific site of the genome in a highly precise manner using specific nucleases. Amongst various GE tools, CRISPR (Clustered regularly interspaced short palindromic repeats)/ CRISPR-associated protein 9 (Cas9) has been found to be the most efficient one in creating site-specific changes/ modifications in the genome of an individual. Genome editing technique offers great potential for speedily developing crop varieties with enhanced nutrient-use efficiency, resistance to various biotic and abiotic stresses and in modifying the nutritional profile. In a recent study, CRISPR/Cas9 technique has been demonstrated to efficiently edit two phytoene desaturase (PDS) genes involved in carotenoid biosynthesis in banana cv. Rasthali (Kaur et al. 2018). Recently in April, 2022, Government of India developed a policy framework for commercialization of genome edited plants by exempting particularly, the SDN1 (site directed nucleases1) and SDN2-genome edited plants from biosafety assessment process as is currently being opted for transgenic crops (ISAAA 2022). This policy framework would encourage the scientists to expedite their research endeavour for developing genome-edited plants. Further, Indian Council of Agricultural Research (ICAR), New Delhi has initiated a network project on developing genome-edited rice, maize, wheat and Indian mustard. Efforts are being made to lower down the glucosinolate content of Indian mustard seed cake using CRISPR/Cas9-mediated genome editing at National Institute of Plant Genome Research, New Delhi.

Maintenance breeding

It is imperative to multiply initial available small quantity of seed of a variety after release, in such a way that its true-to-type seed reaches to the farmers with original genetic make-up. Multiplication of seed is achieved through a series of steps, starting with nucleus seed production followed by breeder, foundation and certified seed production. The mode of reproduction of a crop determines its genetic composition, which, in turn, is the deciding factor to develop suitable seed production technology for maintaining genetic purity during continuous seed multiplication cycles. The cardinal principle of maintaining genetic purity of the seed of a crop is based upon prevention of contamination from different sources. Genetic make-up of a variety gets deteriorated over a period of time due to several factors such as developmental variations, natural crossing, mutations, selective influence of diseases, minor genetic variations and technique of plant breeder beside mechanical mixture (Kadam 1942).

To ensure continuous supply of the true-to-type seed of a variety to the farmers, certain principles and practices are followed which often referred to as maintenance breeding. Laverack (1994) defined variety maintenance as 'the perpetuation of a small stock of parental material through repeated multiplication following a precise procedure'. The maintenance breeding programme helps in purification and maintenance of a variety and its nucleus seed production results into extension of life of a variety. Singhal (2003) recommended control of seed source, preceding crop, isolation, rouging, grow-out test and field inspection to maintain the genetic purity through preventing sources of contamination. Adequate isolation, depending on the mode of reproduction of the crop prevents contamination by natural crossing or mechanical mixtures. Roguing of the seed plots, prior to the stage at which they could contaminate the seed crop, periodic testing of varieties for genetic purity, avoiding genetic shift by growing crops in areas of their adaptation only, certification of seed crops to maintain genetic purity and quality seed and adopting generation system and grow-out test lead to maintenance of the genetic purity of the variety. In India, it is three generation of seeds multiplication, viz., breeder, foundation and certified seed.

Agronomic principles

Selection of agro-climatic region, selection of seed plot, isolation of seed crops, frequency of rouging, certification standard and methods/crop stages for each crop are as per Indian Minimum Seed Standards 2013 (Trivedi and Gunasekaran 2013). The other requirements such as preparation of land, selection of variety, seed treatment, time of planting, seed rate, method of sowing, supplementary pollination, weed control, disease and insect control, nutrition, irrigation, harvesting and drying of seeds are almost similar to that of growing a good crop for production.

Among the food crops under the study, rice, wheat (cereals), mungbean, urdbean, chickpea, lentil and fieldpea (pulses) are self pollinated crops. Maize, sorghum, pearl millet among the cereals and pigeonpea among the pulses are cross pollinated. Therefore, the methods of maintenance varied. Yadav et al. (2022) have illustrated in detail the role and methods of maintenance breeding in field crops.

Maintenance of a self-pollinating variety

Single plants or panicles (true-to-the variety) are selected, harvested and threshed individually and seed is screened for seed characteristics. Plants/panicles having variant seed or seeds are rejected. Seeds from selected individual plant/panicle are planted in 1-2 row *i.e.*, plant-to-row or panicle-to-row and row/s are critically screened at different growth stages. The row/s with variant plant (s) is discarded as and when detected. Single plants typical of the variety are again selected from the remaining rows (for the next cycle of maintenance breeding). The rows are harvested and threshed individually. The seeds are again screened for varietal traits. Seed packets typical of the variety may be bulked to constitute NSS-I or may be used for sowing in NSS-II plots, if nucleus seed requirement is high.

Maintenance of a cross and often cross-pollinated variety

In often cross-pollinated crops, there is a certain amount of out-crossing depending upon flower structure and pollination agents. Therefore, the produce of single plant rows cannot be taken as nucleus seed, as there might be some cross-contamination from adjoining variant rows detected after pollination. So the plant row method is further modified to reserve/rest seed method where single plant seed, after screening, is divided into two parts maintaining its identity. One part is used for evaluation in plant rows, while the other one is kept in laboratory as reserve seed. The reserve seed packets of the plants which have true-to-type progeny (as evaluated in plant rows) are bulked to constitute nucleus seed. This method has been found very effective in purification and maintenance of pigeon pea varieties. In highly cross-pollinated crops like maize and pearl millet the cultivars are mainly open-pollinated varieties or synthetics or composites; a certain level of gene frequency for desirable traits is maintained following the Hardy-Weinberg Law. So, the cultivars are maintained in isolation with random mating (no selection of single plants). In such crops, some amount of variation is acceptable as it is a part of the variety. Successful adoption of marker-assisted selection (MAS)-derived varieties depends on the appropriate after-release follow-up, particularly in maintenance breeding. Unlike other varieties, the maintenance breeding of MAS-derived varieties involves testing genetic purity of the seeds through gene-based/gene-linked markers for the homozygosity of the target allele(s) for tolerance or stress resistance. This follow-up step is very important not only at the nucleus and breeder seed production levels but also during the certified seed production, for the maintenance of seed quality (Singh et al. 2019).

Maintenance of inbred lines of crosses pollinated species

Inbred lines are derived through rigorous (seven to eight) cycles of selfing and/or sib-mating and thus are considerably homozygous. The goal in inbred line maintenance is to maintain the performance and appearance (physical and genetic purity) of original lines through proper isolation, rigorous elimination of off-types (roguing), care in pollination procedures (selfing or sibbing) and using accurate pedigree records and labels. Now-a-days, the majority of cultivars in maize, pearl millet and sorghum are hybrids, where maintenance procedure is applied on parental inbred lines as purity of hybrids is governed by purity of its constituent inbreds. Inbred line maintenance can be accomplished through self-pollination and/or sib-pollination. Inbred lines showing extreme inbreeding depression may be maintained by sib-mating or a combination of selfing and sib-mating. Selfing helps in maintaining inbreds in homozygous condition, while sib-mating tends to prevent excessive loss of vigour. For example, in selfing, representative plants of the inbred lines are self-pollinated and those with uniform characteristics with the inbred description are harvested individually. Ears consistent with inbred characteristics are shelled separately. In the next year, parts of the seeds of individually shelled ears are sown as ear-to-progeny rows. Off-type rows are eliminated and rows with characteristics consistent are selected and self-pollinated. Self-pollinated cobs are harvested individually and off-types are rejected. Ears are shelled separately. A portion of seeds is retained separately, to be used for future progeny testing, and the rest is bulked as nucleus seed.

Alternatively, out of bulked seeds, inbred line is planted. Off-type plants are rogued out before flowering and followed by sib-mating, which is pollination between plants within a row. Moreover, both plant-to-plant as well as bulk sib-pollination are practiced. Plant-to-plant sib-pollination is safer. Inbred lines can also be maintained in isolation, allowing for open pollination after thorough roguing of off-types. True-to-type plants are retained and involved in sib-mating. Off-type ears are rejected after harvest. True-to-type cobs are shelled in bulk. Seeds from best cobs are retained and used as nucleus seed, whereas the rest is used as breeder seed. The most convenient way of maintaining inbred lines is to grow them in a big seed plot in isolation and execute rigorous roguing at four stages of crop growth, *i.e.*, at knee-high stage, flowering, post-flowering and harvest. The cobs of all plants are covered with silk bag before silk emergence. Once the breeder is sure that all off-type plants are rogued out of the seed plot, the silk bags are removed and open pollination is allowed to take place. After harvest, selection is made on the basis of ear and grain characters. One hundred best representative ears constitute breeder's seed after bulking the seeds. Out of the selected 100 ears is retained separately, to be used for future progeny testing, and the rest is bulked as nucleus seed. Out of the selected 100 ears, 50 to 75 seeds are bulked to make up nucleus seed. The rest of the ears harvested from the seed plot are bulked to constitute breeder seed. In the whole process, extreme care is taken to rogue out off-type plants to encourage homogeneity in the material (Singh et al. 2003).

Maintenance of composites/OPVs

Open-pollinated varieties (OPVs) refer to a collection of individuals which share a common gene pool. Synthetics have been derived through interbreeding of lines with good general combining ability, while composite varieties are interbred populations in advanced generation of promising genotypes without any knowledge of their combining ability. Open-pollinated varieties (OPVs) are easier to develop than hybrids; their seed production is simpler, relatively inexpensive and is adapted to the local environment. The subsistence farmers who grow them and can save and exchange own seed for planting in the following season, reducing their dependence on external sources. OPVs are particularly suitable for tribal and hilly regions, where seed replacement rate is very low. In the case of OPVs, care must be taken for actual representation of the variety. Only off-type plants should be removed to minimize inbreeding depression. The number of plants to be used to advance generation is dependent on two factors: the number of plants required to adequately representing the variety and the quantity of the seed required to meet the future seed requirements. Mild selection during seed production and multiplication is inevitable; however, it should be minimized.

Varietal maintenance is normally done in isolation following half-sib method. Fifty to 100 seeds are to be bulked from each cob from representative plants of the variety to form nucleus seed. About 5000–10,000 seeds are normally sufficient to represent OPVs and provide adequate quantity of nucleus seed (Singh et al. 2003).

Seed chain and recent trends in varietal replacement rate

Indian seed systems and regulatory mechanisms for seed quality control have earlier been discussed (Chauhan 1 et al. 2016b; 2000a,b; 2021a,b). et al. (2017) compared Indian and international systems of seed certification and quality assurance to facilitate and promote export of seed from India. The seed chain of cereals, comprising rice, wheat, maize, sorghum and pear millet, barley and finger millet and pulses consisting of mungbean, urdbean, pigeonpea, chickpea, fieldpea, lentil and others during 2020-21, comprised a total of 667 and 310 varieties/ hybrids, respectively (https://seednet.gov.in-weblink). In the present paper, varietal replacement rate (VRR) was assessed as the contribution of varieties in the seed chain released during the last 10 years (2011-2020) to the breeder seed indent, a relaxation of five years is allowed in the guidelines for pulses. Therefore, the share of such varieties developed during 11-15 years was also assessed. Scenario of varietal replacement in seed chain based on breeder seed indents for the year 2020-21 is illustrated in Fig. 2, which revealed that seed chain

Fig. 2. Number of varieties of food crops in breeders' seed chain categorized into different periods of their release and their contribution (based on number) to total number of varieties in breeder seed chain (2020-21)

of pearl millet, maize, chickpea, mungbean, lentil and field pea were dynamic as the share of old varieties (released prior to 2006) was less than 25%, *vis-a-vis* more than 40 % share of latest varieties (released during 2016-20). On the other hand seed chain of pigeonpea and cluster bean may be termed as dormant as the share of old varieties (released prior to 2006) was more than 30%, which turned to be more than 50% when ten year old (released prior to 2010) varieties were taken into account, simultaneously, share of latest released (2016-20) varieties was merely 26% in pigeonpea (Fig. 2) almost nil in cluster-bean. Seed chain of other food crops including rice, wheat, sorghum, barley, finger millet and urdbean may be termed as latent, looking the share of old varieties between 25-50%.

In cereals, contribution of varieties released during 2011-20 to total breeder seed indent in the seed chain of 2020-21 varied from 12.6% for sorghum to 83.8% for wheat. Among the pulses, highest and lowest contribution was for lentil (90.8%) and blackgram (61.3%), respectively (Table 2). The topmost five varieties in the seed chain and released during 2011-20, replacing the old varieties, in various crops along with their contribution to breeder seed indent during 2020-21 are presented in Table 2.

Current scenario of seed production

Production of adequate quantity of quality breeder seed is vital for effective seed production chain and very essential for enhancing crop production. The details are given in Table 3. Kumar et al. (2017) reported that barley production was declined in India as a consequence of reduced demand of breeder seed. In this context, during 2019-20 and 2020-21 breeder seed production was higher than the respective indents for all the cereals and pulses (except cowpea and other minor pulses in both the years and urdbean during 2020-21). The availability of breeder seed was higher by 74.9%-77.9% for cereals and 13.9%-18.9% for pulses (Table 3) as has also been recorded earlier (Chauhan et al. 2016 c; 2000b). Wheat among cereals and chickpea in pulses were the principal contributors to the total foundation seed availability during 2019-20 and 2020-21 with share of 68.0% and 64.1%; 59.1% and 64.0%, respectively. During 2020-21, overall foundation seed requirement was higher by 39.8% for cereals and 18.7% for pulses as compared to that of 2019-20. Nevertheless, the requirement for foundation seed was substantially reduced for maize (-33.3%) and barley/others (-8.3%) during 2020-21(https://seednet.gov.in-weblink). In other cereals, enhancement in seed requirement varying from 0.0% (sorghum and pearl millet) to 100.0% (rice) was recorded during the same period. Foundation seed requirement was higher for all the pulses except urdbean (-1.4%) during 2020-21 in comparison to that of 2019-20. The increase ranged from 10.5% for fieldpea to 87.3% for pigeonpea (Table 3). Availability of foundation seed during 2020-21 was higher by 14.8% for total cereals but lower by 8.3% for pulses as against that of 2019-20. Except rice and barley, there was reduction in foundation seed availability during 2020-21 for majority of cereal crops ranging from 0.3% (wheat) to 37.1% (barley/others). Similarly, in pulses, the foundation seed availability was lower for all the crops except pigeonpea and cowpea/others. The reduction was the highest for fieldpea (26.9%) and the lowest for chickpea (8.6%). Despite these annual fluctuations in foundation seed requirement and availability, during 2020-21 over that of 2019-20, the availability was always higher than the requirements during both the years, for all the cereals except maize, where a deficit of 5.6% (2019-20) and 8.3% (2020-21) was observed. Overall, the increase in foundation seed availability for cereals was 122.2% and 82.2% over the requirements, respectively, during 2019-20 (ranging from 45.9% for barley/others to 138.9% for rice) and 2020-21 (ranging from 42.9% for sorghum to 1100.0% for pearl millet).

During the corresponding period, the foundation seed availability was always more than the requirement for all the pulses except fieldpea during 2020-21 with an overall increase of 47.4% (ranging from 31.7% for chickpea to 207.7% for mungbean) during 2019-20 and 13.8% (ranging from 0.7% for chickpea to 1800.0% for pigeonpea) during 2020-21. Foundation seed is the first stage of downstream conversion of breeder seed. Availability of abundant foundation seed is indicative of vibrant formal seed production chain (Chauhan et al. 2017; 2021b) that may lead to production of adequate quantity of certified/quality seed available to the stakeholders was higher during 2020-21 than that of 2019-20 for rice, wheat and maize by 8.3%, 6.4% and 7.8%, respectively. But lower by 16.0% and 0.5% for sorghum and pearl millet, respectively. Seed of barley and minor millets distributed during 2020-21 registered an increase of 11.5% over that of 2019-20. Overall, seed distributed for cereals during 2020-21 was higher by 7.0% over that of 2019-20 (Table 3). Quality seed of pulses distributed during 2020-21 showed an overall decline of 4.3% in comparison to 2019-20. There was increase in seed distribution for pigeonpea (1.9%), urdbean (10.5%) and lentil (12.4%) whereas; chickpea, mungbean, fieldpea and cowpea/other minor pulses registered a decrease of 7.1%, 0.8%, 14.0% and 6.0%, respectively. Of the total 421.09 lakh q of quality seed for all field crops distributed during 2020-21, cereals and pulses accounted for 58.4% and 7.8%, respectively. The corresponding values were 59.9% and 8.9% during 2019-20. But, overall seed distributed during 2020-21 was higher by 9.7% than that of 2019-20 (Table 3). The results of the present study corroborated the earlier findings on distribution of certified/quality seed of food crops during the last decade and that was responsible for enhanced production (Chauahn et al. 2016 c; 2020b)

Seed requirement and availability

Cereals

Analysis of seed requirement and availability during the last 11 years (2010-11 to 2020-21) revealed that seed requirement for cereals has increased consistently by 31.6% from 186.8 lakh q during 2010-11 to 245.8 lakh q during 2020-21 (Anonymous 1 2021). Although, the requirement was higher over the base year yet dipped marginally during 2012-13 as compared to that of 2011-12 and during 2015-16 in comparison to 2014-15. The availability of quality seed of paddy, wheat, maize, sorghum, pearl millet and other cereals was always higher than the requirement except for wheat during 2010-11 and 2013-14 (Fig.3). Nevertheless, the deficit was only 2.4% and 3.6%, respectively. Overall, availability of quality seed during this period was increased by 42.1%

during 2020-21. However, the availability was reduced by 7.8% and 8.8% during 2018-19 and 2019-20, respectively, but increased by 2.1% during 2020-21 as compared to that of 2017-18.

The seed availability showed a consistently increasing trend during the last 11 years for almost all the crops and the highest was achieved for rice (104.1 lakh q); maize (15.7 lakh q) and barley/small millets (4.1 lakh q) during 2017-18 (Anonymous 2021, 2022), while the highest availability of quality seed for wheat (151.4 lakh q) was during 2020-21; sorghum (3.6 lakh q) during 2013-14 and pearl millet (4.3 lakh q) during 2012-13 (Fig. 3). During 2020-21, the contribution of rice, wheat, maize, sorghum, pearl millet and barley/small millets to the total availability of seed was 22.5%, 31.3%, 3.3%, 0.6%, 0.6% and 0.9 %, respectively. Similar results were

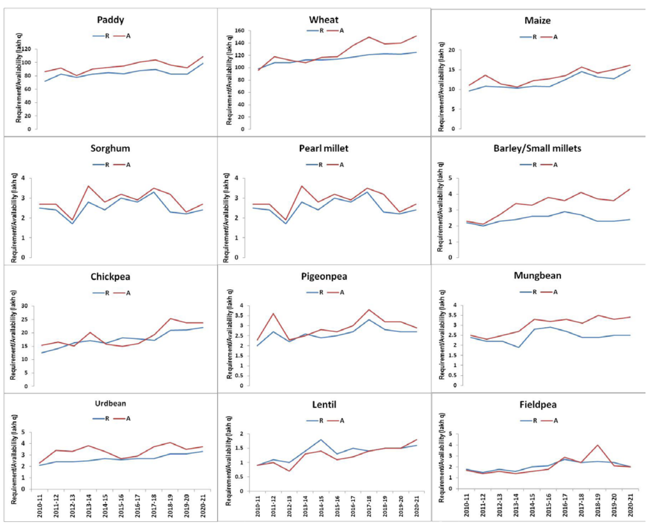


Fig. 3. Seed requirement (R) vs availability (A) in lakh q of major food crops from 2010-11 to 2020-21

also reported earlier (Chauhan et al. 2020b)

Pulses

Ali et al. (2016) assessed the total seed requirement of pulses as 33.0 lakh q at 30% seed replacement rate. The seed requirement for major pulses has shown consistent and appreciable increase over the last 11 years from 2010-11 to 2020-21 (Anonymous 2021), registering an increase of 62.3%. Seed requirement for pulses during the last 11 years increased gradually up to 2016-17 but declined marginally by 1.3% during 2017-18. No consistent pattern of increase or decrease was discernable for individual pulse crop. The availability of quality seed also showed a corresponding increase from 25.9 lakh q (2010-11) to 43.6 lakh q (20018-19), an increase of 68.3% during the last 11 years but decreased by 9.4% during 2019-20 and 2020-21 over that of 2018-19 but still higher by 54.1% over the base year (Fig. 3). The seed requirement for *rabi* pulses like chickpea during this period surged by 74.6%, during 2020-21 and the deficit between requirement and availability was 7.4%, 2.5%, 17.7% and 9.6% in the years 2012-13, 2014-15, 2015-16 and 2016-17, respectively. Nevertheless, the availability of seed was higher than the requirement by 17.6%, 16.9%,17.5%, 12.2%, 21.1%,12.8% and 7.6%, respectively, during 2010-11, 2011-12, 2013-14, 2017-18, 2018-19, 2019-20 and 2020-21. Lentil seed requirement increased by 100.0% from 2010-11 to 2014-15 and deficit between seed requirement and availability ranged from 7.2% (2013-14) to 30.0 % (2012-13) except years 2010-11, 2017-18, 2018-19, 2019-20 and 2020-21 when seed availability was either *at par* with or higher than the requirement. The deficit between seed requirement and availability for fieldpea ranged between 1.5% (2020-21)-19.9% (2014-15) except for the years 2016-17, 2017-18 and 2018-19 while the requirement surged by 50.0% during 2016-17 over that of 2010-11) but reduced by 11.1%, 7.4%, 11.1% and 23.6% during 2017-18, 2018-19, 2019-20 and 2020-21, respectively, over that of 2016-17.

For *kharif* pulses like pigeonpea, mungbean and urdbean abundant seed was produced and availability was always higher than the requirement except for pigeonpea during 2013-14 when requirement was higher by 2.3% than the availability. The highest seed requirement for pigeon pea (3.3 lakh q); mungbean (2.9 lakh q) and urdbean (3.3 lakh q) was recorded during 2017-18, 2015-16 and 2020-21, respectively. The increase was 65.0%, 20.8% and 47.6%, respectively, over the base year (2010-11) for pigeonpea, mungbean and urdbean, during the period. Chauhan et al. (2016c; 2020b) reported similar pattern of seed requirement and availability for *rabi* and *kharif* pulses earlier. New initiatives for development, especially for pulses, such as creation of 150 seed hubs since 2016-17 and strengthening 12 centres in major pulses growing states led to enhanced breeder seed production and maintenance of seed chain of newly released varieties that had great impact on enhanced availability of quality seed and thus production of pulses (Chauhan et al. 2016c; 2020b). Chauhan et al (2020a) also reported similar observations for enhanced yield of rapeseed-mustard and other oilseeds.

Impact of breeding programmes on yield and production of food crops

Success or strength of breeding programme of each crop was assessed on the basis of two criterion; (1) Number of varieties available in seed chain for each one lakh ha area and, (2) share of top 10 varieties in the seed chain. Breeding programme of rice followed by wheat were most effective as 0.80 and 0.56 varieties/ lakh ha area of cultivation and share of top 10 varieties was 27.4% and 55.6 %, respectively, in rice and wheat (Fig. 4). Breeding programme of maize and pearl millet were found least effective among food crops because merely 0.37 and 0.22 varieties/ lakh ha area were available.

Simultaneously, share of top 10 varieties was 76.4% and 94.8%, respectively, reflecting dominance of few varieties in seed chain.

Efficient breeding programme coupled with dynamic/latent/dormant seed production chain resulted in spectacular gains in production and yield in rice and wheat (Fig. 4). Similar gains were observed with moderately efficient breeding programme along with dynamic seed chain (mungbean and lentil) and with moderately efficient breeding programme coupled with latent seed chain (chickpea and pigeonpea). Decline in production of sorghum may be the outcome of dormant seed chain, hence may be improved by increasing the efficiency of seed chain through inducting latest released varieties. Decline in yield was observed in urdbean only, which may be accounted for moderately efficient breeding programme coupled with latent seed chain, however it provides greater scope for improvement through increasing seed chain efficiency. In spite of less efficient breeding programme coupled with latent seed chain in maize and pearl millet, spectacular gains were observed in yield of both crops, which may be accounted for the availability of dominant share in seed availability from private seed sector. It is suggested that breeding programme and seed chain under public sector provide large scope for further improvement in production and yield of these crops. New plant breeding technologies are a key element in making food systems more productive and sustainable. Future plant breeding endeavours should aim at solving the major current hurdles, mainly: (i) bridging the genotype–phenotype gap by improving quantitative and automated selection and screening methods; (ii) bridging the genome–environment gap: since many desired plant traits depend on the interaction of many genes and metabolic pathways with the environment (Altman 2021; Martin 2021).

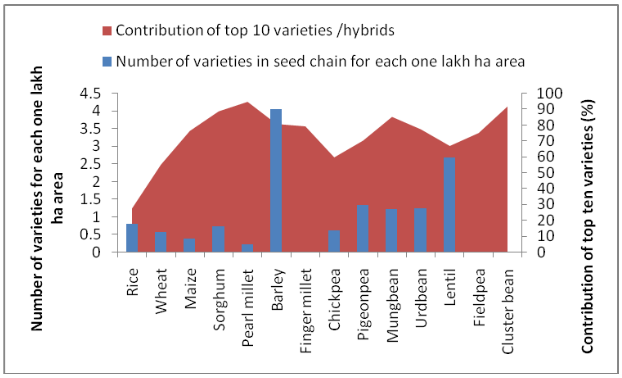


Fig. 4. Number of varieties available for each one lakh ha area and contribution of top ten varieties to total breeder seed indents

Output of enhanced SRR, VRR and policy interventions

In food crops, continuous surge in seed requirement could be due to enhanced knowledge among the stakeholders, especially farmers, about the need of seed replacement, through concerted and planned efforts for skill up-scaling. Chauhan et al. (2016b; 2020b) reported significant progress in the production of breeder and certified/quality seed of food crops as a consequence of ICAR-Mega seed project launched during 2005-06 and National Mission on Agricultural Extension and Technology initiated during XII plan. The timely and adequate availability of good quality seed was evidenced by increased distribution of certified/quality seed during the last 11 years. Further, there was rapid increase in induction of recently released high yielding and climate resilient varieties in the seed chain of cereals and pulses, consequently, enhanced varietal replacement ratio (VRR). These systematic efforts have led to the increased seed replacement rate (SRR) and surpassing even the ideal level for major cereals and pulses during the period under study (Chauhan et al. 2020b), consequently, higher seed yield/ha and thereby production (Fig. 5). There was negligible increase in area of cereals (1.0%) but the production and yield/ha increased by 25.0% and 23.7%, respectively, during 2020-21 over 2010-11 (Fig. 5). The production of rice, wheat, maize, pearl millet and pulses during 2020-21 increased over that of 2010-11 by 27.4%, 26.0%, 45.2%, 4.4% and 41.3%, respectively, with concomitant enhancement of productivity by 21.2%, 15.9%, 25.9%, 33.1% and 29.1%, respectively (Fig. 5). However, production of sorghum decreased by 31.7% during the corresponding period, despite increased seed yield/ha by 18.9% over that of 2010-11. This could be because of declining acreage under sorghum from 7.38 m ha in 2010-11 to 4.24 m ha during 2020-21, a reduction of 42.5%. In pearl millet also, there was marginal increase in production despite spectacular increase in yield/ha by 33.1% as the area was appreciably reduced by 21.3% (Fig. 5). Pulses production and seed yield/ha during the last 11 years increased during 2020-21 over that of 2010-11 by 41.0% and 29.1%, respectively. The pulses production appeared to increase on account of both increase in area as well as yield/ha (Fig. 5). Nevertheless, among the pulses, acreage under lentil was reduced by 9.4% but there was no impact on production due to enhanced yield/ha. On the contrary, high production of urdbean was attained due to

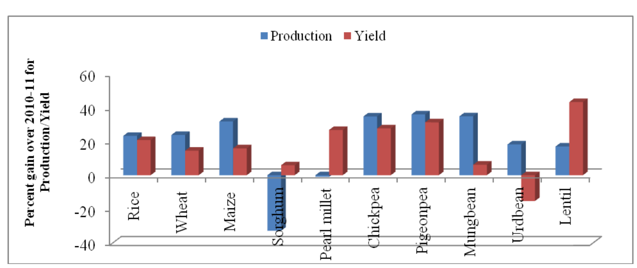
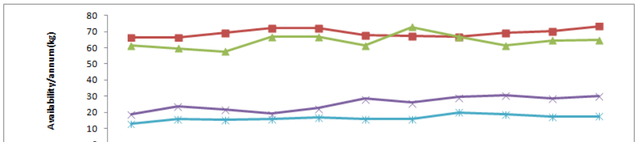


Fig. 5. Patterns of changes in area, production and yield of major food crops during 2020-21 over that of 2010-11

considerable increase in acreage despite decline in yield/ha (Fig. 5). In chickpea, pigeonpea and mungbean increase in area, production and yield/ha was recorded during 2020-21 over that of 2010-11(Fig. 5).

The increased production of food grains resulted in to high per capita net availability/annum of food grains despite increased population from 1.21 billion (2011) to 1.31 billion (2017) during this period (Anonymous 2021, 2022). For rice, per capita net availability/annum was the highest during 2020 (73.4 kg) and increased by about 10.5% in comparison to the base year (Fig. 6). Per capita net availability of wheat increased up to 72.9 kg during 2016 registering an increase of 18.7% over that of 2010 but thereafter continuously declined by 8.6%, 15.6%, 11.4% and 11.1% during 2017, 2018, 2019 and 2020, respectively (Anonymous 2021; 2022). Nevertheless, in these years, net per capita availability was also higher by 0.2% (2018) – 8.6% (2017) in comparison to that of 2010 (Fig. 6). Per capita net availability/ annum of coarse cereals and pulses increased considerably during 2020 by 66.5% and



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Rice	66.4	66.3	69.4	72.1	72.3	67.9	67.2	66.8	69.2	70.1	73.4
Wheat	61.4	59.7	57.8	66.8	66.8	61.3	72.9	66.7	61.5	64.6	64.8
Other cereals	18.8	23.9	21.9	19.2	22.6	28.4	26.1	29.4	30.6	28.6	30.3
Pulses	12.9	15.7	15.2	15.8	16.9	16.0	15.7	20.0	18.7	17.2	17.5

Fig. 6. Per capita net availability of food grains during 2010-2020

35.7% over that of 2010 (Anonymous 2021; 2022).

During the last 70 years, India became major exporter of food grains in the world market from ship-to-mouth situation in 1960's and has been producing surplus rice, wheat and maize over the years. During the decade (2010-11 to 2019-20), rice export increased by 305.6% and wheat from almost zero to 0.22 mt, several thousand folds. Nevertheless, maize export reduced drastically by 87.7% (Fig. 7). Contribution of basmati rice to total rice export in terms of quantity and earnings ranged from 31.0% to 99.6% and 53.9% to 98.1%, respectively, during this period.

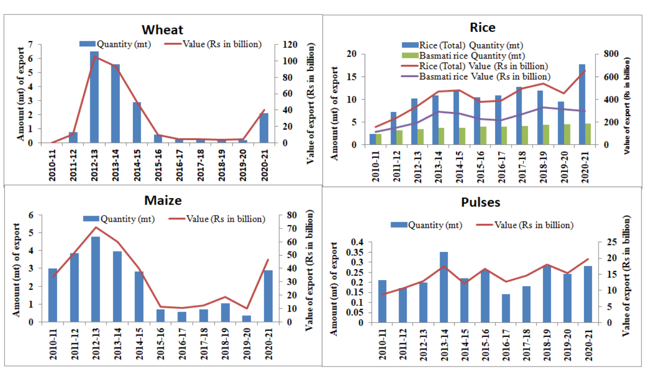


Fig. 7. Trends in export of food grains during 2010-11 to 2020-21

The highest foreign exchange earnings were achieved for rice during 2020-21 (US$ 8.82 bn), wheat (US$ 1.93 bn) and maize (US$ 1.30 bn) during 2012-13. India also achieved near self sufficiency in pulses during this decade and staggering import bill was reduced substantially by 58.1% from ₹ 285.2 bn (2016-17) to ₹ 119.4 bn (2020-21). During 2021-22, foreign exchange worth ₹ 158.29 bn (US $ 2.12 bn) has been achieved from the export of 7.23 mt of wheat; ₹ 729.65 bn (US $ 9.67 bn) from 21.21 mt of rice, ₹ 76.15 bn (US $ 1.02 bn) from 3.69 mt of maize and ₹ 26.79 bn (US$ 0.36 bn) from 0.39 mt of pulses (http://agriexchange.apeda. ov.in-weblink; http://tradesta.commerce.gov.in-weblink).

Strategic policy intervention to sustain food security

With almost six-fold increase in food grain production from 50.8 mt in 1950-51 to 310.74 mt in 2020-21, India has moved away from dependence on food aid to become a net food exporter. However merely producing sufficient food grains cannot ensure food security. Government policies largely determine the public access to available food grains. Narayanan (2015) reported access to food, to be a serious issue especially in the context of extraordinarily high-inflation rates in food commodities and to high-quality diets. Khera (2010) advocated public distribution system, for food security in rural areas. The National Food Security Act (NFSA 2013) envisions a comprehensive legislative framework for protecting an individual's right to food, furthering the vision expressed in the Constitution of India. The NFSA 2013 aims at to ensure food and nutrition security for the most vulnerable through its associated schemes and programmes, making access to food a legal right. In 2016, the government of India launched a number of programmes to double farmers' incomes by 2022 seeking to remove bottlenecks for greater agricultural productivity. These include, the National Food Security Mission, Rashtriya Krishi Vikas Yojana (RKVY), the integrated schemes on Oilseeds, Pulses, Palm oil and Maize (ISOPOM) now merged with National Food Security Mission, Pradhan Mantri Fasal Bima Yojana and the e-market place. The government has taken significant steps to fight undernourished and malnutrition over the past two decades, such as through the introduction of mid-day meals at schools, anganwadi systems to provide rations to pregnant and lactating mothers, and subsidized grain for those living below the poverty line through a public distribution system. Mahsa et al. (2020) advocated for some food subsidy programmes that can improve the food security status in developing countries. Isnarti (2020) suggested combining government programmes with household and women programmes such as giving subsidy for small and poor household, giving food to children and subsidizing grain for farmers and creating home garden to achieve food security in India. Government of India is contemplating to launch a National Nutrition Mission by 2022 to address the issues of malnutrition in children and lactating mothers that also envisions promotion of bio-fortified varieties. Further, Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government envisions to fully subsidizing breeder seed of field crops released within the last 10 years.

Suggestions

We have been witnessing the environmental degradation caused by increased level of CO2 and other green house gases, climatic variations incited drought and salinity conditions, increased level of pollutants and nitrogenous compounds from industrialization, rise in temperatures etc. Damages caused by these factors and the changes in dynamics of diseases and insect pests are likely to make higher negative impact on global food production. There are growing concerns about our ability to increase crop yield and quality further or even sustain it under the changing environmental scenario. To achieve the targets of increased production of cereals and pulses, science based holistic approach is needed to adopt and execute sooner than later as the situation is already aggravated by degrading natural resources and low total factor productivity.

The current situation demands the breeders to devise alternate agronomic management approaches to improve food production, sustain yields with lower consumption of inputs including water. Specific selection strategies, assessment of genotypes at several locations and over the years to get genotypes with stable yields are needed to enhance and sustain the yield. Expanding the genetic base by creating new germplasm lines through various techniques such as mutations, introgression of novel alleles from landraces and wild relatives are very essential. Pyramiding of multiple resistance genes against pests and diseases through marker-assisted selections, understanding the component of complex traits through high throughput technologies, transfer of genes across genera through transgenic approaches are some of the approaches likely to improve yields.

As per National Council of Applied Economic Research (NCAER), the estimated growth rate in India during 2016-24 for rice, wheat, coarse cereals and pulses is likely to be 2.46%-2.75%, 0.96%-1.73%, 0.41%-3.30% and 2.74%-3.21%, respectively as against population growth of 1.10%. Technological advances needed to achieve these targets are high yielding varieties with high genetic yield potential and its realization through integrated crop management practices. Further, chickpea is the leading pulse contributing about 46.6% to the total pulse acreage during 2020-21 but the SRR was lower than the requisite one. Similarly, in maize, sorghum and pearl millet, largely hybrids are grown; therefore, there is an urgent need for increasing as well as sustaining SRR. A dormant/inert seed chain need to be energized and activated so that farmers can reap the gains of high yield potential of recently released varieties and,can pass the benefits to the consumers as well. Late adoption of a variety in some states happens due to their policy of insisting for evaluating centrally released varieties in their state adaptive trials for one or two years, which may be avoided as the variety has already been tested at some locations of that state under crop specific AICRP. Merely excluding an old variety on the basis of its ten/fifteen year after release will ultimately affect the farmers and consumers interests. Phasing out mega varieties, which have completed 10 years or so but still popular among the farmers should be done very systematically in a gradual manner and not abruptly. For example, wheat variety HD 2967 (just completed 10 years of release) and Pusa Gautami (which will complete 10 years by 2023),chickpea variety JAKI 9218 (released in 2008), mungbean variety IPM 02-3(released in 2009) etc. should not be discontinued just because these have completed 10 years of release. Similarly, in rice, Cottondora Sannalu and MTU 7029 were released well before 20 years, Pusa 1121 (released in 2005) and Swarna Sub 1 (released in 2009) were among the top five varieties in the seed chain during 2020-21.Before calling them off, it has be analyzed critically why these varieties are still popular and widely grown by the farmers despite a large number varieties were released afterwards. Similar considerations have to be put in place for mega varieties in other crops, as well.

Seed is the critical input for realizing the potential yield of varieties and thus seed production of newly developed varieties is vital. Special attention should be given to bio-fortified varieties, which need immediate large-scale seed production and distribution for speedy spread among the farmers and their effective distribution among the consumer through the public distribution system to address the issue of large scale malnutrition. Indian seed sector is strong enough to take up the challenges through its well knit system of seed production and distribution and only need is to keep it energized through complementarities in sharing resources and responsibilities among stakeholders both from public and private sector and enabling policy support from the government.

Authors' contribution

All authors contributed equally.

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