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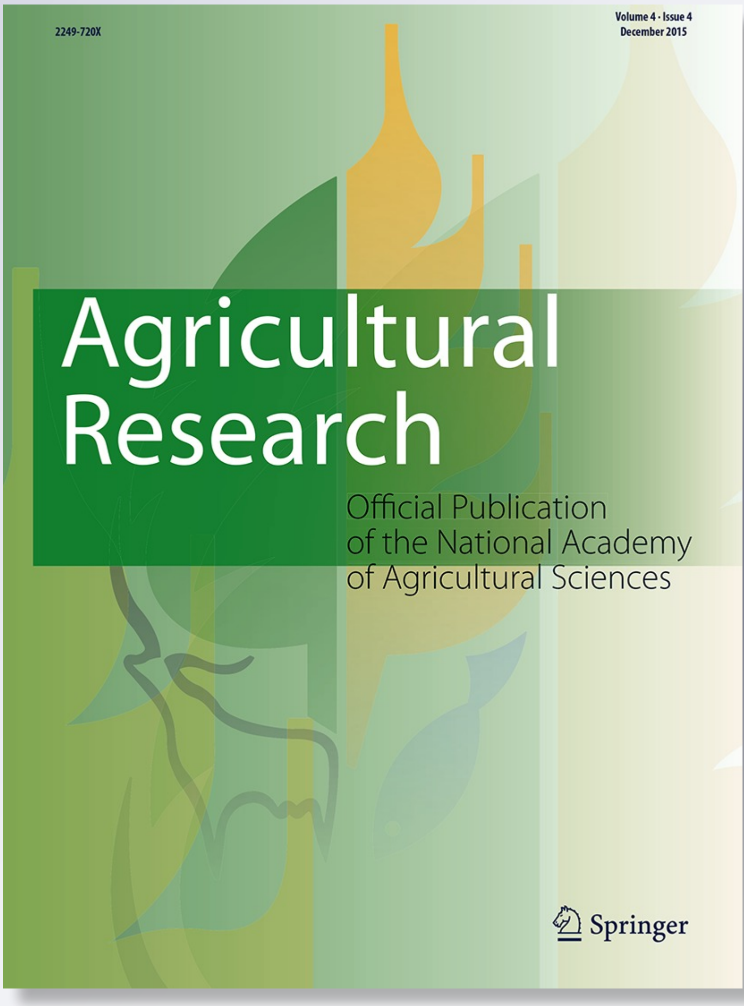

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REVIEW

Genetic Improvement of Maize in India: Retrospect and Prospects

O. P. Yadav[1] · Firoz Hossain[2] · C. G. Karjagi[1] · B. Kumar[1] · P. H. Zaidi[3] · S. L. Jat[1] · J. S. Chawla[4] · J. Kaul[1] · K. S. Hooda[1] · P. Kumar[1] · P. Yadava[1] · B. S. Dhillon[4]

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Abstract Maize (*Zea mays* L.) is the third most important crop of country after rice and wheat and is cultivated round the year. Its grain is used as feed, food and industrial raw material. Enormous progress has been made during last six decades to enhance yield potential through genetic improvement and alleviate effects due to various biotic- and abiotic-stresses. This review presents an overview of strategies followed in genetic improvement of maize and assesses their impact on productivity and production of the crop. A diverse range of indigenous and exotic germplasm and breeding material have been utilized. Breeding programme has been very vibrant and various strategies viz., composite breeding, double cross, three way cross and single-cross hybrid breeding have been adopted in cultivar development to enhance productivity across a range of production ecologies. Since 2000, more than 165 high-yielding cultivars of different maturity periods and types [field corn, sweet corn, baby corn and quality protein maize] having adaptation to different agro-ecological zones have been released. Development of cultivars having tolerance to abiotic-stresses (water and temperature extremes) and resistance to diseases has been a priority area in maize improvement. Both conventional and molecular approaches have been and continue to be used in development of disease resistant, stress adapted and nutritionally superior cultivars. In order to realize full potential of improved cultivars, agronomic research has targeted several management interventions like plant density, mineral fertilization, water management, resource conservation and various maize-based cropping systems across different ecologies. Improved products have been delivered to farmers by both public and private sectors involved in maize seed production and distribution. As a result, area under improved cultivars has been increasing consistently, and currently approximately 65 % of maize area is under improved cultivars (mostly hybrids). Adoption of high-yielding cultivars, improved production technology and increased demand of maize resulted in increased production (from 1.7 to 24.4 million ton) and productivity (from 547 to 2583 kg/ha) from 1950–1951 to 2013–2014. Future prospects of maize cultivation and improvement strategies in context of climate change and in providing nutritional security are also discussed in this review.

Keywords Maize production · Breeding priorities · Hybrids · Disease resistance · Insect resistance · Drought tolerance · Cold tolerance · Abiotic stress tolerance · Water logging · Nutritional security · Genetic improvement · Germplasm · Specialty corn · Quality seed production

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Introduction

Maize (*Zea mays* L.) is cultivated on 184 million ha in 165 countries with a global production of 1016 million ton and productivity of 5.52 ton/ha [21]. It has emerged as the cereal with the largest global production, which surpassed rice in 1996 and wheat in 1997, and its production is increasing at twice the annual rate of rice and three times that of wheat [22].

India grows maize on 9.0 million ha and occupies fourth rank after the United States (35.5 million ha), China (35.3 million ha) and Brazil (15.4 million ha). Maize is the third most important crop in India after rice and wheat [84]. Its grain is used as feed, food and industrial raw material (Fig. 1). It is cultivated round the year in the country, though most of it (83 %) is grown in rainy or *kharif* season (July to October) followed by winter or *rabi* (November to April) (15 %) and spring (February to May) (2 %) seasons. The most important maize growing states are Karnataka, Andhra Pradesh, Maharashtra, Tamil Nadu, Rajasthan, Bihar, Uttar Pradesh and Madhya Pradesh, which account for more than 80 % of the total maize area of the country and also account for similar share in production. As a food crop, maize has more diverse utilization pattern as compared to other major crops because an array of products are developed from it, and several types of maize like quality protein maize (QPM), sweet corn, pop corn, baby corn, etc. are available.

Both area and production of maize have been steadily increasing since 1950 (Fig. 2). The area has increased from 3.3 to 9.0 million ha and production from 1.7 million ton to 24.4 million ton in 2013–2014. The increase has been very rapid in the last 10 years as a result of increase in productivity and expansion of area due to spread of its cultivation in Andhra Pradesh, Karnataka, Maharashtra and Tamil Nadu. On the other hand, the area showed declining trend in recent years in the states of Madhya Pradesh, Uttar Pradesh, Jharkhand and Punjab. In India, maize traditionally is a *kharif* season crop, but its cultivation is now increasing in *rabi* and the spring seasons.

Owing to its cultivation in diverse ecologies of the country, maize is subjected to various abiotic and biotic stresses. These include moisture and temperature extremes, diseases and insect-pests. Concerted efforts have been made to alleviate the effects of these stresses and to enhance yield potential through genetic improvement and improved management. Consequently enormous progress has been made in this direction during last six decades. This review presents an overview of strategies followed in genetic improvement of maize in India and assesses their impact on productivity and production of the crop. In addition, future prospects of maize cultivation and improvement strategies in context of climate change and in providing nutritional security are also discussed.

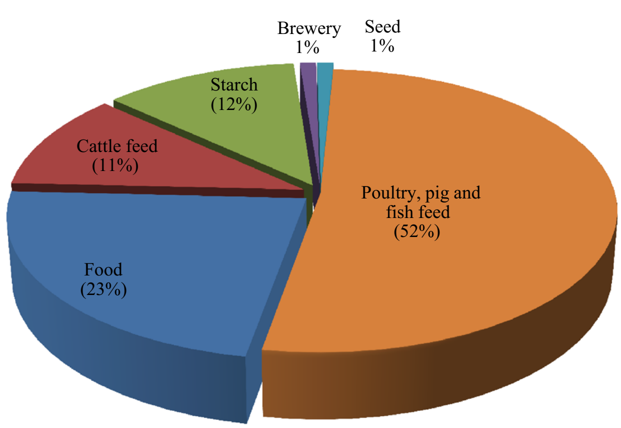

Fig. 1 Utilization pattern of maize grain in India

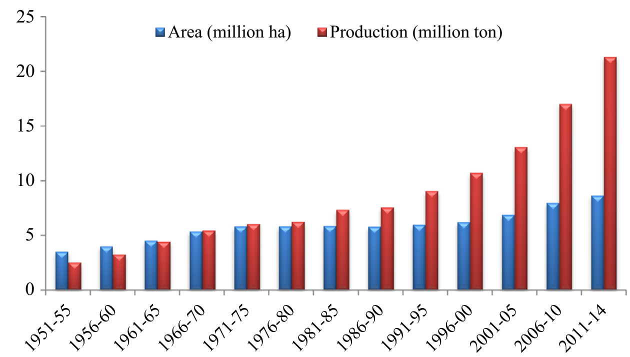

Fig. 2 Trends in area and production of maize in India since 1951

Genetic Improvement

Germplasm Collection, Introduction and Utilization

Availability of diverse germplasm is a pre-requisite for undertaking a successful crop improvement programme. Intensive efforts were made to collect indigenous variability as well as to introduce exotic germplasm. Studies showed that landraces with primitive characteristics exist in Himalayan region, which were termed as 'Sikkim Primitives' [10] and are different from primitive Mexican races, viz., Nal-Tel and Palomero [48]. Consequently, extensive efforts were made for collection of germplasm from the North Eastern Himalayan NEH region. Based on the evaluation of these collections and other germplasm, the Indian races of maize were classified as primitive, advanced, recent introductions and hybrid races [64]. Besides races, there were several important local varieties, named usually after the region where they were predominantly cultivated. Important locals included Anantnag, Bassi, Chamba, Coimbatore, Hyderabad, Jalandhar, Jaunpur, Kulu, Malan, Rudrapur, Sathi and Sikkim.

The indigenous germplasm were tall, low yielder and largely of flint type. It had limited variability as compared to exotic germplasm especially from central and South America. Even then, indigenous germplasm had special significance as these were evolved in balance with the prevalent agro-ecological forces and, therefore, is expected to possess better adaptation to regional stresses. Indigenous germplasm were used to develop populations, heterotic pools and inbreds [12]. Molecular characterization of local germplasm depicted the diverse nature of maize germplasm in India [46, 53, 57, 63, 69, 83].

Germplasm from many countries particularly the USA, Mexico, Colombia, Peru, Venezuela and Caribbean islands were also introduced in 1950s under Rockefeller Foundation. With the establishment of International Maize and Wheat Improvement Center (CIMMYT) in 1966, the germplasm flow to India gained momentum. Some introductions were used directly as commercial cultivars such as composites viz., Laxmi and Suwan 1, released in Bihar state, and some like Tuxpeno, Suwan 1, Suwan 2, Antigua Gr 1, Eto, Stiff Stalk Synthetic, Lancaster Surecrop, CI21E (CM 202) as source material to develop inbred lines and heterotic pools [12].

Presently, about 10,000 accessions (indigenous and exotic collections) are under long-term conservation in the National Gene Bank at the National Bureau of Plant Genetic Resources, New Delhi. Majority of the exotic germplasm is of tropical and subtropical origin. Characterization of some of these germplasm for specific traits such as biotic- and abiotic-stresses, and nutritional quality parameters helped in identifying more than 30 sources with unique traits which are of immense use in breeding programme.

Breeding Priorities and Cultivar Development

Local landraces were cultivated and maintained up to early 1950s. The agriculture practices during that period were of subsistence nature. Maize research during the period was confined to a few state agricultural departments with little-trained manpower. Hence, the early research in maize largely concentrated on the improvement of local landraces and traditional cultivars. In addition, efforts were also made to enhance the maize productivity through cultivation of introduced hybrids like US 13, Dixie 18, Texas 26, NC 27 and Illinois 1656 from the USA in early fifties. However, the introduced hybrids had poor adaptation due to their temperate background [11]. Indigenously developed hybrid, viz., Punjab Hybrid 1 was released in 1956 in the state of Punjab; however, it failed to gain popularity due to seed production problems. The productivity of maize in 1950s was around 0.6–0.8 ton/ha, and average rate of improvement between 1951 and 1956 was only 27 kg ha^{-1} $year^{-1}$ (Fig. 3).

Systematic research on maize in India was initiated with the establishment of the All-India Coordinated Maize Improvement Project (AICMIP) in 1957. This was the first such initiative by the Indian Council of Agricultural Research (ICAR) to promote and share germplasm and experiences among maize workers and to undertake multi-locational and multidisciplinary evaluation of experimental varieties to identify cultivars adapted to diverse ecology of the country. The multi-location evaluation also shortened the time of experimentation and enhanced the reliability of evaluation. Since then maize improvement programme has evolved very strongly and adopted several strategies to enhance crop productivity in order to meet the increased demand of maize. This model of all India research project has been adopted in other food, fodder and fibre crops.

With the establishment of AICMIP, efforts were initiated on development and evaluation of multi-parent hybrids. In 1961, four double cross hybrids, namely Ganga 1, Ganga 101, Ranjit and Deccan were released for commercial cultivation. Focus on multi-parent continued and a new set of elite hybrids were released, out of which Ganga Safed 2, HiStarch and Ganga 5 were widely adopted by farmers.

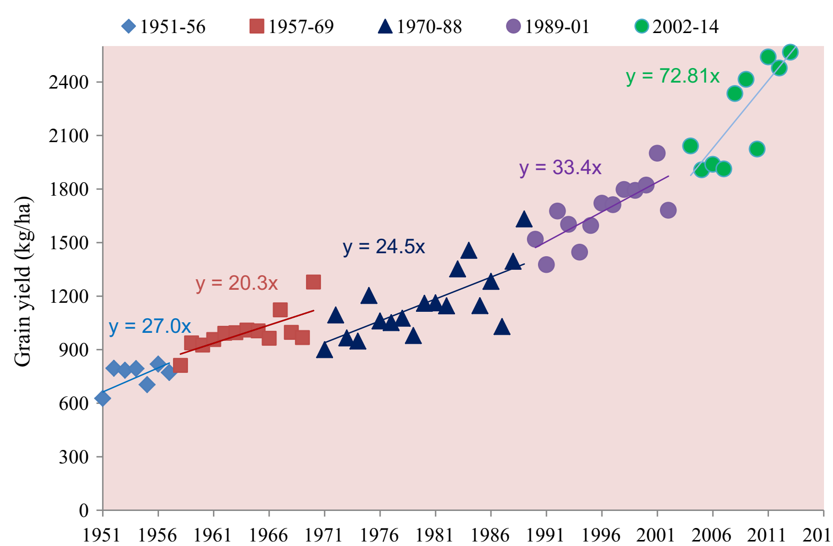

Fig. 3 Trend of improvement in maize productivity (kg/ha/year) in India during different periods from 1951 to 2014

Realizing that hybrid seed production is a challenging job, Government of India established the National Seeds Corporation (NSC) in 1963 to undertake hybrid seed production. However, the production and supply of quality hybrid seeds to farmers at the right time remained a major challenge because of poor vigour and yield of inbred parents and consequent difficulties in seed production. High cost of hybrid seed and susceptibility of the hybrids to leaf blight, and *Pythium* and *Erwinia* rot were other factors which limited the adoption of these hybrids. Further, the time coincided with the era of 'green revolution' in the country and more focus was given by NSC to supply quality seeds of pureline varieties of rice and wheat, the seed of which was much easier to produce than that of hybrids. Consequently, there was no improvement in growth rate of maize productivity during 1957–1969 in comparison to growth rate of 1951–1956 (Fig. 3).

Maize improvement strategy was, therefore, given a relook, and the strategy of composite breeding was adopted in addition to multi-parent hybrid breeding, however for some years composite breeding became the main focus. First, a set of six composite cultivars, namely Amber, Jawahar, Kisan, Vijay, Vikram, and Sona were released in 1967. Realizing that a large area was under rainfed cultivation, the composite breeding programme gave more emphasis on early maturity. The first set of early maturing composites, Ageti 76 in Punjab and Tarun at the national level were released. Among composites, Vijay, Kisan and Ageti 76 were widely adopted. On the whole during 1970–1988, more than 50 composites, 10 double- and double-top cross hybrids were released. In the early 1980s, focus of breeding programmes shifted to hybrid breeding. As a result, first three-way hybrid, Trishulata was released in 1991 and first single cross hybrid (SCH), Paras was released in 1995. This was followed by the release of three SC hybrids: Parkash, Pusa Early Hybrid Makka 1 and Pusa Early Hybrid Makka 2. The improvement in maize yield during this period occurred at slightly higher rate than that achieved in the three previous periods (Fig. 3).

Since 2000, more than 165 high-yielding cultivars of different maturity/durations namely, extra-early, early, medium and late; and types (field corn, sweet corn, baby corn and QPM) developed by public and private sectors have been released for commercial cultivation in different agro-ecological zones/across zones. Public sector mainly targets less-endowed environments particularly the rainfed ecology where maize crop encounters more risks, whereas private sector focuses on better-endowed environments having higher productivity potential and assured seed marketing. In this period, the major emphasis has been on SC hybrid breeding, and more than 80 SCHs have been released. Some of the public-bred hybrids are Buland, DHM 117, HM 10, HM 11, PMH 1, PMH 3, Sheetal, Vivek Hybrid 21, Vivek Hybrid 43, etc. There is a continuous expansion of area under high-yielding private-sector hybrids especially under good agronomic conditions. The spread of private-sector hybrids was further facilitated by strong seed production programme and aggressive marketing. The popular private-sector hybrids include Bio 9681, Bio 9637, NK 6240, Pinnacle, 30 V 92, DKC 9108, 900 M Gold, PAC 740, PAC 751, RMH 4726 and Seed Tech 2324. Maize productivity increased @ 73 kg/ha/year during 2002–2014 which is more than double the improvement rate achieved during 1989–2001 (Fig. 3).

Improving Nutritional Quality

Lysine and tryptophan contents are low in maize protein making it nutritionally poor. An impetus to enhance nutritional quality in maize in India was provided with the discovery of nutritional benefit of recessive *opaque2* (*o2*) that increases lysine and tryptophan by 2–3 folds, compared to normal maize [44]. The breakthrough prompted the introgression of *o2* allele into a series of elite genetic background. These efforts led to the successful development and release of three *o2* composites, viz., Shakti, Rattan and Protina during 1971. However, these nutritionally enriched maize cultivars could not become popular, primarily due to their chalky appearance and negative pleiotropic effects of *o2* such as soft endosperm that made *o2*-based cultivars more prone to attack of stored grain insect-pests. Desirable combination of endosperm modifiers into *o2* background at CIMMYT, Mexico resulted in hard endosperm-based *o2* genotypes [80]. In India, accumulation of modifiers especially from CIMMYT germplasm led to the release of first hard endosperm-based *o2* composite, Shakti-1 in 1997. With the increased focus on hybrid breeding, the first QPM hybrid in India, 'Shaktiman-1' (a white kernel-based three-way cross) was released in 2001, followed by 'Shaktiman-2' (a white kernel-based SCH) in 2004. The first yellow-kernel-based SCHs, 'Shaktiman-3' and 'Shaktiman-4' were released together during 2006, followed by 'Shaktiman-5' in 2013. These QPM hybrids were specifically adapted to Bihar state. Later, a number of single-cross QPM hybrids were released with wider adaptability to different agro-ecologies of the country [9].

With the initiation of application of molecular markers for maize improvement in India [55], utilization of SSR markers to select *o2* allele, coupled with marker-based background selection, led to the commercial release of first marker-assisted selection (MAS) maize product (Vivek QPM-9) during 2008 [26]. In 2012, MAS-derived Vivek QPM-21, a single-cross QPM hybrid was released for the state of Uttarakhand. Currently, markers are being utilized for accelerated development of QPM hybrids in quality breeding programmes. QPM version of parental inbreds of several commercial single-cross maize hybrids have been developed, and experimental hybrids are currently under testing for evaluation of agronomic performance. To further increase lysine and tryptophan in the endosperm, *opaque16* (*o16*) is being introgressed in *o2* genetic background in the quality breeding programme. Mutant combination of *o2* and *o16* offers possibility of enhancement of lysine by 40–80 % as compared to only *o2o2* genotypes [86].

Enhancing vitamin-A of maize is a recent focus in India. Although traditional yellow maize possesses tremendous natural variation for carotenoids [70, 71, 78], the carotenoids are predominated by lutein and zeaxanthin, which possess no provitamin-A activity [81]. The major provitamin-A carotenoid viz., β-carotene is present in minute concentration. Multi-location evaluation of a large set of yellow maize inbreds revealed that β-carotene level in maize kernel is 0.1–2.0 ppm [82], which is below the targeted level of 15 ppm [6]. A rare allele of *β-carotene hydroxylase* (*crtRB1*) that increases the concentration of β-carotene by blocking its conversion to further components [85], has been introgressed into seven elite parental inbreds using MAS. Reconstituted version of hybrids showed enormous increase in kernel β-carotene, with a mean of 17.5 ppm, while it was 2.1 ppm among the original hybrids [49]. Research efforts to develop multi-nutrient rich maize has also been initiated in India. Provitamin-A-rich version of a QPM hybrid is currently under multi-location testing. Besides, rare allele of *lycopene epsilon cyclase* (*lcyE*) that forces lycopene flux towards β-carotene branch [28], is also being introgressed along with *crtRB1* for further enrichment of β-carotene in the genetic background of commercially available QPM hybrids [25].

Research on development of maize with high iron (Fe) and zinc (Zn) mineral densities has also been initiated in India. Analyses of large set of maize inbreds of Indian and exotic origin indicated ample scope to improve the level of Fe and Zn through breeding [3, 7, 24, 54]. Identification of QPM inbreds with high Fe and Zn further provides additional benefits for harnessing high lysine and tryptophan in the endosperm [42]. Genome-wide analyses for Zn-transporters could localize some key genes responsible for accumulation of Zn in maize kernel [47]. In addition, marker-assisted introgression of low phytate mutant (*lpa-2-2*) into elite normal maize inbreds has been undertaken to enhance the bioavailability of Fe and Zn [73, 74]. The results are encouraging as these MAS-derived lines possess sufficiently low phytate level.

Specialty Corn

Demand for specialty corn has increased by many folds in recent times. Among various types, sweet corn has emerged as one of the most important specialty corn types that is mainly used as fresh and processed vegetables and snack items [68]. The first sweet corn composite named ‘Madhuri’ was released in 1990. Further efforts to develop diverse sweet corn cultivars led to the development of some more sweet corn cultivars like Priya, Win Orange and HSC 1. Efforts are now underway to develop sweet corn hybrids in the genetic background of *sugary1* (*su1*) or *shrunken 2* (*sh2*) [36, 37]. Identification of closely linked SSR markers for *su1* and *sh2* has further provided new dimension for marker-assisted introgression of these alleles in elite genetic background [29].

Cultivation of pop corn and baby corn is also coming up well specially in the peri-urban area. The first baby variety, VL-78, was released in 2004. A few number of pop corn composites were also released by the public sector organizations. Quantitative trait loci (QTL) have been identified for various popping traits in maize, thereby providing opportunity to introgress these into elite flint genetic background through MAS [5].

Starch has been one of the important by-products of maize grain and currently 12 % of the maize produced is used in starch industry. A three-way cross hybrid ‘Histarch Hybrid Makka’ rich in starch was released in 1993. Recently, HM-13, a SCH having higher starch content in grain has been released. Further, diverse waxy corn inbreds (~100 % amylopectin due to *wx1* allele) have also been generated and are being used in the breeding programme. Genetically diverse high oil maize inbreds have been developed, and they possess significance in the variety development, as feed with high oil content is desirable in the poultry industry.

Efforts made to develop maize cultivars suitable for fodder production to cater to the need of mixed crop-livestock farming system led to the release of green fodder variety African Tall in 1982 for the entire country. In 1997, composite APFM-8 was released for cultivation in south zone of the country. Further, J-1006 (for Punjab) and Pratap Makka Chari 6 (for Punjab, Haryana, West UP and Rajasthan) were released in 1992 and 2008, respectively. Continued popularization of sweet corn and baby corn cultivars additionally provides new dimension to the farming system, as they provide sufficient fodder after the harvest of the ears.

Improving Disease and Insect-Pest Resistance

Although more than 30 diseases have been reported from different regions of India, important ones are turcicum leaf blight (TLB: *Exserohilum turcicum*), maydis leaf blight (MLB: *Drechslera maydis*), post-flowering stalk rots complex (PFSR: *Fusarium verticilloides, Macrophomina phaseolina*), banded leaf and sheath blight (BLSB:

Rhizoctonia solani f. sp. *sasakii*), sorghum downy mildew (SDM: *Peronosclerospora sorghi*), rajasthan downy mildew (RDM: *Peronosclerospora heteropogoni*), bacterial stalk rot (BSR: *Erwinia chrysanthemi* p.v. *zeae*) and brown stripe downy mildew (BSDM: *Sclerophthora rayssiae* var. *zeae*) [52]. The incidence of these diseases is encountered in different agro-ecological regions depending on prevalent climate (temperature, rainfall and humidity), cultural practices (planting density) and diversity of maize cultivars. Under favourable conditions, these diseases cause immense losses to both quantity and quality of grain produced [52]. Host-plant resistance breeding has been in focus, as employing host-plant resistance is sustainable and cost effective. Following good understanding of epidemiology of different pathogens, field screening techniques have been developed which are able to differentiate resistant and susceptible lines and are being used extensively in resistance breeding programmes. Evaluation of large and diverse germplasm under artificial epiphytotic conditions and/or sick plots has resulted in identification of resistant sources for TLB, MLB, PFSR, RDM and BSDM. QTL have been identified conferring resistance to SDM, RDM [50] and BLSB [23] that should enable precise deployment of these loci in new materials. In addition to exploiting host-plant resistance, cultural and chemical measures have also been developed to control these diseases. However, chemical control measures are largely restricted to seed production plots and to seed treatment of commercial hybrid seed sold to farmers.

Three insects, namely stem borer (*Chilo partellus*), pink stem borer (*Sesamia inference*) and shoot fly (*Atherigona sp.*) are key pests in India. These are being controlled generally through application of insecticides. In addition, germplasm are being continuously evaluated under artificial infestation to identify resistant sources against these insect pests. Antigua Group 1 has drawn attention over a long period as a resistant source. It was also used as a male parent (CM 500) of hybrid Ganga 5. Recent efforts to improve moderately resistant sources through cyclic selection and inbreeding under artificial infestations have been reasonably effective in reducing leaf injury. Resistance to pink borer among inbreds is also reported [59]. Maize grains after harvest are also infested by a wide array of stored insect pests, of which rice weevil (*Sitophilus oryzae*) and Angoumois grain moth (*Sitotroga cerealella*) have emerged as the voracious feeders of cereal grains. In developing countries like India, grains are generally stored in jute bags which often absorb moisture during rainy season and create favourable conditions for weevil infestation [72]. Large-scale screening of diverse inbreds including QPM, pop corn and sweet corn have led to the identification of resistant sources against rice weevil infestation [30]. These resistance sources hold promise for their objective utilization in the breeding programme. Further, biological control through *Trichogramma chilonis* has gained importance during recent years. Integrated pest management strategy can also provide solutions for sustainable control of the insect pests.

Enhancing Abiotic Stress Tolerance

Maize is largely (over 80 %) grown as rainfed crop during rainy season and moisture availability is seldom adequate for *kharif* maize. The crop is also prone to face contingent/intermittent excessive moisture/water logging or drought at critical growth stages, and occasionally both within same crop season. *Rabi* maize area is often restricted (15 %) due to prolonged low (<10 °C) temperature regimes in the months of December and January in most parts of India, except in south. Cold stress at critical growth stages, especially at early vegetative and flowering stages may cause irreversible physiological damages on maize plants [41, 45], which eventually results in severe yield losses [39].

Climate change effect, which is clearly experienced in terms of increased frequency of weather extremes, is offering further challenges to an already sub-optimal/challenging environment. Several climate modelling studies suggest sharper increase in both day- and night-time temperatures, heavy and concentrated rainfall within limited days causing water-logging for short periods and leaving severe dry days in rest of the season in the Asian tropics. This is clearly demonstrated in a recent analysis by Indian Meteorological Department using past 110 years (1901–2011) weather data [4] which indicated that although there is no significant change in total rainfall, but in recent years, the number of rainy days has reduced significantly, which resulted in episode of extremes of moisture availability. Such changes are already being felt in a number of real and recognizable ways in different maize growing regions, in terms of shifting seasons, and higher frequency of extreme weather events, such as drought, water logging and heat coupled with emergence of new/complex diseases.

Drought Tolerance

Most of the work on drought stress have been largely restricted to multi-location evaluation of newly developed maize varieties under rainfed stress-prone environments. A systematic work on drought initiated during late 1990s led to the identification of most susceptible/critical crop stage(s) for drought, morpho-physiological traits associated with drought tolerance [87] and identification of promising sources for drought tolerance [15, 16]. Managed drought stress phenotyping has been the major strategy in selection of drought tolerance. Keeping in view the target environment and sensitivity of the stress, drought stress phenotyping and selection have focussed on flowering/early grain-filling stage drought [87]. Key stress-adaptive traits have been identified as shorter anthesis-silking interval (ASI), more number of ears per plant (EPP), stay green, less leaf rolling, and small tassel size [20, 89]. Promising drought tolerant lines derived from various populations viz., Early maturity Pool 16 BN Seq., Pool 18 Seq., DTPW-C9S3, DTPY-C9S3 yellow, La Posta Seq. C7 S2 have been identified [16, 19] and are being used in breeding for drought tolerance.

Water Logging

Research on excessive moisture (water-logging) tolerance was initiated with screening of large set of germplasm for assessing their responses against water-logging conditions. Germination and seedling stage followed by early vegetative stage are the most susceptible to water logging [94]. Susceptibility decreases at later crop stages, especially after flowering. Stress-induced early adventitious root formation, high root porosity, minimum loss in chlorophyll, reduced senescence, ASI of <5 days and low plant mortality are identified as stress-adaptive traits associated with water-logging tolerance [31, 79, 88, 93]. The cup-screening method has been developed and standardized, which is quite effective and efficient for preliminary screening of large number of maize germplasm against excess soil moisture stress [93]. Only selected entries are then taken for validation under field conditions, as managing uniform water logging in larger plots has always been a challenge. Studies on mechanism of water-logging tolerance suggested that both avoidance of anaerobiosis by maintaining the oxygen supply through formation of above ground nodal roots and large parenchymatous space in cortical region of root tissues, and tolerance to anaerobiosis through metabolic adjustments are important features for the adaptation to excessive moisture [90]. Genetic analyses suggested that both additive and non-additive gene actions are important for water-logging tolerance in tropical maize. However, additive gene action is comparatively more important, which along with heterosis significantly contribute to water-logging tolerance [32, 92]. Genetic variability and promising germplasm with reasonably high level of water-logging tolerance have been identified [14, 94] and further improved. A water-logging tolerant synthetic population was developed involving elite lines with high general combining ability for water-logging tolerance [91].

Keeping in view the *kharif* maize environment, where maize crop faces both drought and water-logging stress within same crop season, efforts have been made to identify traits to select for combined stress tolerance. Genome-wide association analyses and expression assay further led to the identification of single nucleotide polymorphisms (SNPs) and candidate genes in maize under water stress conditions [75, 76].

Cold Tolerance

During 1980s, work on cold tolerance was initiated for developing low temperature (non-freezing) tolerance in maize with special focus on early growth stages [13, 39]. Germplasm were identified and further improved for early seedling and vegetative stage cold tolerance [38], and promising cold tolerant hybrids viz., Sheetal and Buland and composite viz., Partap were released.

Cold stress at flowering stage causes severe yield losses due to reproductive failure. Efforts have been made to assess effects due to cold stress on maize and traits associated with cold injury or cold tolerance leading to discovery of genotypic variability for cold stress in tropical maize [13, 95]. A large set of maize germplasm, including lines from various AICMIP centres and CIMMYT's tropical highland maize programme have been evaluated under cold stress. Promising lines with reasonably good level of cold tolerance for both vegetative and flowering stages were identified for using in cold stress tolerance breeding programme [17].

Improved Management

High productivity is a synergistic effect of improved cultivars and crop management. Agronomic research has targeted several management interventions, namely plant densities, mineral fertilization, water management, resource conservation and profitability of various maize-based cropping systems across different ecologies in order to harness the full potential of improved hybrids in their target ecology.

Plant population per unit area has increased over years. Under intensive management, higher plant population (80,000–90,000 plants/ha) is remunerative, while a lower plant population (60,000 plants/ha) has been recommended for rainfed ecology [67]. Response to 150 kg N/ha, 75 kg P_2O_5/ha, and 75 kg K_2O/ha has been reported in *kharif* season [62, 65]. During *rabi* season, hybrids have responded to 250 kg N/ha, 105 kg P_2O_5/ha and 105 kg K_2O/ha [27, 51]. Recent studies in better-endowed environments have shown that application of N in 5 splits (10 % at basal, 20 % at V4, 30 % at V8, 30 % at flowering, and 10 % at grain filling) results in significantly higher grain yield as compared with earlier standard recommendation of three equal splits at sowing, knee high (V4) and pre-flowering (V8) stages [66]. The application of neem-coated urea has been found to enhance N-use efficiency [18]. Besides the major nutrients, maize also responds to zinc application @ 25 kg/ha.

Conservation agriculture (CA) practices are sustainable, resource use efficient and improves soil health besides providing opportunity for practicing intensive cropping system [77]. CA has drawn attention of maize agronomists in India since long (zero tillage was recommended as early as 1979 in Punjab), but it has now gained importance because of environmental concerns and escalating fuel prices. In recent years, zero tillage system has created good impact in rice–maize cropping systems in peninsular India especially in coastal Andhra Pradesh [77].

Management of water is the key issue in all maize production ecologies as both moisture extremes are harmful. In rainfed ecology, conservation of moisture through various techniques forms critical intervention. These techniques include mulching by disturbing topsoil or applying organic sources and using low plant populations. The studies in *kharif* season have shown that residue retention increases maize yield by 6 %, while crop residue along with fungal consortium application gave 14 % higher yield over no residue application [18]. Water management is equally important in irrigated maize. Seedling, knee high, flowering and grain-filling stages are the most sensitive for water requirement [65].

Maize provides ample opportunities for intensified inter- and sequential cropping systems, and suitable cropping systems have been worked out for diverse agro-ecologies [35]. The important maize-based cropping sequences involving baby corn and sweet corn with pulses, oilseeds, vegetables and flowers have helped in increasing cropping intensity up to 400 % [8, 61].

Quality Seed Production

To fully harness the advantages of improved hybrid cultivars, a well-organized seed production programme is essential. Compared to hybrids and composites, inbred lines need different production technology package like crop geometry, and nutrient and water management because of less vigour. Earlier, agronomy of inbred parents did not get much attention. During last two decades, not only agronomy of inbred lines got due attention, but also a good progress has been made in the development of high-yielding inbred lines. Besides, there has been vast improvement in terms of modernization of seed processing and packaging.

Both public and private sectors are involved in maize seed production and distribution. Public sector supplies the breeder and foundation seed of parental lines of hybrids to the private sector besides producing certified hybrid seed. NSC, 15 State Seed Corporations (SSC), several State Department of Agriculture and Agricultural Universities are involved in seed production. Recently, seed village concept has been started in Rajasthan and West Bengal to produce certified seed under Government's special schemes to promote food and nutritional security. However, major share in seed industry is of private sector. Most of the seed production is being undertaken during *rabi* season in Andhra Pradesh due to favourable growing conditions and adequate infrastructure for seed processing.

Public–Private Partnership

Hybrid seed production and marketing of maize hybrids developed by the public sectors are undertaken by public sector organizations, but enough seed is not produced to meet the demand. Therefore, public–private partnership (PPP) between public sector research institutions and small and medium private seed companies has been established for seed production and marketing of public-bred hybrids [84]. This is of great help in achieving rapid dissemination of newly released cultivars and high seed replacement. Another example of PPP is evaluation of private-sector hybrids by coordinated project centres across India. However, the PPP model needs to be reinforced beyond current testing of private-sector hybrids in All India Coordinated Research Project (AICRP) mode, and outsourcing and marketing of seed production of public-bred hybrids by private sector. Future partnership must undertake collaborative germplasm enhancement for various target trait following successful PPP models like Germplasm Enhancement of Maize (GEM) in US, and Tropical Asian Maize Network (TAMNET) in Asia to support development of improved germplasm.

Adoption and Impact of Improved Technologies

The area under improved cultivars has increased considerably over years. Currently, around 65 % of maize area is under hybrids of which 25 % is estimated to be under SC hybrids. The adoption of hybrids has been much higher in *rabi* and spring seasons than in *kharif* season. In *rabi* and spring seasons, weather vagaries are rare, and therefore, crop is cultivated under high level of inputs. Moreover, crop duration is longer. Thus, *rabi* and spring seasons are characterized by assured high productivity. The highest levels of hybrid adoption are in the states of Andhra Pradesh, Tamil Nadu, Punjab, Bihar (*rabi* season) and Haryana (>90 %) while it is low (<30 %) in Rajasthan, Bihar (*kharif* season), Chattisgarh, Madhya Pradesh, Uttar Pradesh and North-Eastern states.

Factors contributing to large-scale adoption of hybrids include (i) high yield and inbuilt disease resistance, (ii)

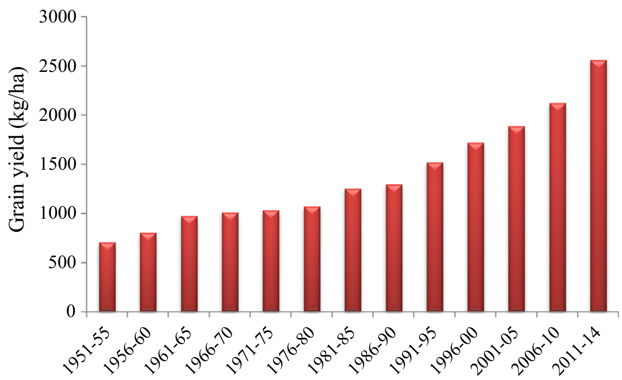

Fig. 4 Mean productivity of maize in India since 1950

availability of hybrids with good adaptation to different agro-ecologies and reasonable tolerance to abiotic-stresses, (iii) highly developed seed sector and economical seed production, and (iv) effective contractual hybrid seed production system, distribution and marketing.

Maize productivity has been consistently increasing in India since 1950 (Fig. 4). Due to large-scale adoption of hybrids and improved production technologies especially during last two decades, maize productivity increased by 98 % which is higher than that of rice (50 %) and wheat (50 %) during 1986–2014 (Table 1). This magnitude of improvement in maize assumes greater significance because of three reasons. Firstly, more than 75 % of maize is grown under rainfed conditions which are much higher than rainfed area under rice and wheat. Secondly, there have been significantly lesser investments, both in terms of human resource and infrastructure, in maize research than wheat and rice research and development. Thirdly, government policy support to maize in form of the minimum support price and assured procurement like wheat and rice is negligible. Thus, high magnitude of yield improvement in maize is a successful demonstration of technology-led growth.

It is often argued that impressive growth of maize in the country is largely driven by the private sector. However, it should be recognized that the private sector has been preferably targeting assured production ecology (like *rabi* season) especially during last decade as this production ecology is risk-free, and there is assured return to farmers on their investment in seed, fertilizer and irrigation. On the other hand, the risky production ecology (like drought-prone *kharif* season in North-Western India) does not find as much favour of private sector as in *rabi* season. In this ecology, public sector has greater role to play and has made much greater contribution, although limited number of hybrids could be scaled-up and delivered during last decade. This is due to inadequate seed production by various state seed producing agencies, lesser investment in marketing by public sector and insufficient seed production research by the public sector.

Continued increase in maize production since 1950 (Fig. 2) has made India now seventh largest exporter of maize. Since 2010, India has been annually exporting 3.5–5.0 million ton and earning foreign exchange worth Rs 4500–7500 crore. From 2001 to 2011, the export has undergone exponential increase from 0.1 to 5 million ton and the Indian share in international maize export increased from mere 0.23–3.35 %. The increased share is due to high competitiveness of the Indian maize grain as compared to others in the international market. The export destinations are primarily South-East Asian countries for which India has an advantage of low freight charges, in addition to being competitive.

Future Prospects

Diversification of germplasm base The continuous enhancement of yield can only be achieved by continuous infusion of more and more diverse elite germplasm from temperate regions. Only a fraction of wide genetic variation available in maize has been exploited so far. Recycling of existing elite lines without disturbing the heterotic groups can further increase the yield in short-term. However,

Table 1 Quinquennial means of grain yield and percent improvement in yield over average yield of 1986–1990 in maize, rice and wheat in India during 1986–2014

Period	Grain yield (kg/ha)			Improvement (%) in yield during the period over that of 1986–1990		
	Wheat	Rice	Maize	Wheat	Rice	Maize
1986–1990	2066	1584	1297	–	–	–
1991–1995	2388	1807	1548	16	14	19
1996–2000	2603	1897	1723	26	20	33
2001–2005	2679	1957	1890	30	24	46
2006–2010	2775	2148	2125	34	36	64
2011–2014	3107	2378	2562	50	50	98

Source DAC, Government of India http://www.agricoop.nic.in broadening of germplasm base with traits like drought and water-logging tolerance, disease and insect-pest resistance, superior nutritional quality, good standability, and traits required for climate resilience will be of particular value to sustain long-term genetic gains in productivity and stability. Exploitation of temperate germplasm has so far received less attention. Temperate material is a potential source of diversification of hybrid-oriented germplasm. The genetic base of specialty maize (QPM, high oil, special starch types, sweet corn, pop corn, etc.) and fodder maize germplasm available with Indian maize breeders is very narrow which needs to be urgently widened.

Acceleration of breeding process Although conventional breeding has been successful in developing a range of elite cultivars, accelerated breeding efforts are critically important to further increase rate of genetic gain to help meet the increasing demand of maize. Several new developments and techniques offer a great prospect of accelerating breeding programme and line development process. One of them is doubled haploid (DH) technology that reduces the inbred development period from 7–8 to 2–3 seasons. Availability of tropicalized haploid inducers with haploid induction rate of up to 10 % [56] having adequate adaptation to tropical ecology offers a great promise. Currently many private seed companies have already integrated in vivo haploid induction in their regular breeding programmes. Indian maize breeding programme needs to be geared-up to embrace latest developments in molecular biology and bioinformatics. High throughput genotyping, genome-wide association mapping, genomics-assisted selection, and decision support tools in maize breeding to manage phenotypic and genotypic data and pedigree records, being used by several institutions worldwide, should be an integral part of Indian breeding programme. Precise phenotyping for abiotic-stresses like drought and heat through proper networking should become an essential and key component to develop new breeding material and necessary stress resilience. Access to good off-season nursery sites is evenly important to reduce the breeding cycle period.

Integration of transgenic germplasm in maize breeding Globally, transgenic germplasm has been extensively deployed in modern maize cultivars. Such cultivars now occupy 57.4 million ha (32 % of global maize acreage) [34] A large number of transgenic germplasm accessions have been imported in India for research purpose through NBPGR. Most of the germplasm have been deployed for introgression of transgenic traits in the locally adapted material. Between 2006 and 2013, over a dozen of transgenic events have undergone field trials. The prominent traits under field trials are herbicide tolerance and insect resistance. While imported transgenic germplasm would accelerate cultivar development, there is a greater need for indigenous efforts for transgenic germplasm development. In recent years, protocols for regeneration and transformation in tropical maize have been standardized [1, 43, 58]. These early leads should be useful in the future efforts for indigenous development of transgenic germplasm for various traits. However, this would first require a strong policy support and then a robust PPP.

Stress-resilient cultivars Agriculture systems, in general, are highly dependent on prevailing weather conditions, and therefore extremely vulnerable to climate change affects. Asian tropics, including India, are projected to experience an increasing frequency of extreme weather conditions with high variability [2, 33]. Therefore, there is urgent need to focus more on stress-resilient germplasm, rather than just on high yields or tolerance/resistance to individual stresses. Keeping in view the weather extremes, especially with high variability and uncertainties, C_4 crops, such as maize, might play major role in coping up with such challenging environment, which can enhance resilience in agriculture. Maize cultivars with increased resilience to abiotic- and biotic-stresses will play an important role in adaptation to climate change of vulnerable farming communities. Biotic- and abiotic-stress tolerance and higher productivity are the way forward for sustainable improvement in maize production to meet current and future demands of maize.

Specialty and health food The demand of specialty and health food is on the rise. Breeding programme needs a greater focus to develop products for target consumer. QPM has a potential role to play in achieving nutritional security and improving health. Available QPM hybrids need to be scaled-up through awareness and food-industry linked programmes. Availability of QPM with higher contents of Vitamin-A, Fe and Zn is likely to be a reality in near future making maize as multi-nutrient grain.

Scaling-up of SC hybrids There exists a tremendous scope to further increase maize productivity in India to make maize cultivation more profitable to farmers. This would require further expansion of area under SC hybrid cultivation as has successfully been done by many other countries like USA, China, Argentina, Brazil, South Africa and Canada. The adoption of SC hybrids along with complete improved package of practices would go a long way to achieve productivity gains like other countries. Bringing entire maize area under SC hybrid cultivation in next 10 years can easily help double the production and make India as large producer and exporter of maize grain, maize seed, and other value-added products. This would also make maize a more competitive crop which is very critical in diversification of agriculture in Indo-Gangetic Plain where rice and wheat are being grown traditionally.

Dual-purpose maize hybrids The availability of agricultural land to meet the growing demand for fodder will continue to be a challenge in coming years. On the contrary, the importance of livestock will continue to increase due to livelihood security especially under the scenario of climate change, erratic rainfall, etc. The focussed efforts to develop dual-purpose maize cultivars which can meet the requirement of both food and stover will be more promising for further increasing the value and acceptability of maize cultivation by farmers. In fact, some initial efforts are underway to identify the existing commercially released hybrids which are most suitable for both grain as well as fodder purposes. Stay-green nature of cultivars would enhance stover quality. Further, development of new baby corn and sweet corn hybrids would also provide opportunity to provide fodders.

Growing maize in non-traditional areas Maize as a crop can also be popularized among farming community of non-traditional areas. For example, since 2001–2002, maize area in the state of West Bengal has increased 2.8 times due to which production has increased by 4.2 times (2011–2012 data accessed from www.indiastat.com). This has been possible due to popularity of maize among farmers over rice, potato and mustard in *rabi* and jute in *kharif* season. In areas where winter rice crop suffers due to water scarcity, maize has emerged as potential alternative [40]. Similarly area of cotton and rice in Karnataka and area of sorghum and cotton in Maharashtra has been diverted to maize. Thus, efforts towards popularization of maize in other non-traditional areas provide ample opportunity for livelihood among farming community.

The demand for maize is expected to rise in coming times. The major drivers of maize demand in India include (1) growing demand from poultry and piggery sectors, consuming more than half of the domestic production, (2) growing urbanization, leading to increased demand for processed foods like corn flakes, bakery products, etc., (3) growing organized dairy sector, requiring more of fine cereals or maize-based concentrates and (4) rising international price due to utilization of maize grain towards biofuel production. The projected growth rates of feed-based industries suggest that maize demand in India is expected to increase from current level of 25 million ton to 45 million ton by 2030. With strengthening of genetic improvement programme coupled with development of suitable agro-interventions and appropriate policies, India should be able to produce more than this target.

References

1. Abhishek A, Karjagi CG, Nath R, Bhardwaj M, Ramteke PW, Kumar P, Dass S, Kumar RS (2014) Differential effect of immature embryo's age and genotypes on embryogenic type II callus production and whole plant regeneration in tropical maize inbred lines (*Zea mays* L.). Indian J Genet Plant Breed 74:317–324
2. ADB (2009) Food security under threat from climate change. http://reliefweb.int/report
3. Agrawal PK, Jaiswal SK, Prasanna BM, Hossain F, Saha S, Guleria SK, Gupta HS (2012) Genetic variability and stability for kernel iron and zinc concentration in maize (*Zea mays* L.) genotypes. Indian J Genet Plant Breed 72:421–428
4. Attri SD (2012) Climate change and agricultural strategies. In: Workshop on climate smart agriculture in Asia: research and development priorities, Bangkok, 11–12 April 2012
5. Babu R, Nair SK, Kumar A, Rao HS, Verma P, Gahalain A, Singh IS, Gupta HS (2006) Mapping QTLs for popping ability in a popcorn x flint corn cross. Theor Appl Genet 112:1392–1399
6. Bouis HE, Hotz C, McClafferty B, Meenakshi JV, Pfeiffer WH (2011) Biofortification: a new tool to reduce micronutrient malnutrition. Food Nutr Bull 32:S31–S40
7. Chakraborti M, Prasanna BM, Hossain F, Mazumdar S, Singh AM, Guleria SK, Gupta HS (2011) Identification of kernel iron- and zinc-rich maize inbreds and analysis of genetic diversity using microsatellite markers. J Plant Biochem Biotech 20:224–233
8. Choudhary VK, Kumar PS, Sarkar SK, Yadav JS (2013) Production potential, economic analysis and energy auditing for maize (*Zea mays*)–vegetable based cropping systems in Eastern Himalayan region, Arunachal Pradesh. Indian J Agric Sci 83:110–115
9. Dass S, Jat SL, Chikkappa GK, Kumar B, Kaul J, Parihar CM, Kumar A, Kumar R, Kamboj MC, Singh V, Jat M, Singh AK (2012) Genetic enhancement and crop management lead maize revolution in India. Maize J 1:7–12
10. Dhawan NL (1964) Primitive maize in Sikkim. Maize Genet Coop Newsl 38:69–70
11. Dhillon BS, Malhi NS (2006) Maize breeding in India: retrospective analysis and prospects. Indian J Plant Genet Resour 19:327–345
12. Dhillon BS, Prasanna BM (2001) Maize. In: Chopra VL (ed) Breeding field crops pp 147–185. Oxford and IBH Publishing Co, New Delhi
13. Dhillon BS, Sharma RK, Malhotra VV, Khehra AS (1988) Evaluation of maize germplasm for tolerance to low temperature under field and laboratory conditions. J Agron Crop Sci 160:89–93
14. Dhillon BS, Thind HS, Malhi NS, Sharma RK (1998) Effect of excess water stress on grain yield and other traits in maize hybrids. Crop Improv 25:209–214
15. DMR (2004) Annual report: 2003-04 Directorate of Maize Research, New Delhi, pp 50-59
16. DMR (2006) Annual report, 2005–2006 Directorate of Maize Research, New Delhi, pp 41–48
17. DMR (2007) Annual report, 2006–2007 Directorate of Maize Research, New Delhi, pp 55–63
18. DMR (2014) DMR Annual report, 2013–2014 Directorate of Maize Research, Pusa Campus, New Delhi 110012, India
19. Dubey L, Prasanna BM, Hossain F, Verma DK, Ramesh B (2010) Phenotypic evaluation of a set of selected exotic maize for drought stress tolerance in India. Indian J Genet Plant Breed 70:355–362
20. Edmeades GO, Banziger BM, Ribaut JM, White JW, Reynolds MP, Lafitte HR (1998) Improving crop yields under water deficits in the tropics. In: Chopra VL, Singh RB, Varma A (eds) Crop productivity and sustainability—shaping the future proceedings of the 2^{nd} international crop science congress, 437– 451. Oxford and IBH, New Delhi
21. FAOSTAT (2013) www.faostat.fao.org (accessed on 18 January 2015)

22. Fischer RA, Byerlee D, Edmeades GO (2014) Crop yields and global food security: will yield increase continue to feed the world? ACIAR Monograph No 158. Australian Centre for International Agricultural Research, Canberra
23. Garg A, Prasanna BM, Sharma RC, Rathore RS, Saxena SC, Rao HS, Pixley K (2008) Genetic analysis and mapping of QTLs for resistance to banded leaf and sheath blight (*Rhizoctoniasolani* f sp *sasakii*) in maize.In: Proceeding of the 10th Asian regional maize workshop, Makassar, Indonesia. 20–23, October 2008, pp 211–214
24. Guleria SK, Chahota RK, Kumar P, Kumar A, Prasanna BM, Hossain F, Agrawal PK, Gupta HS (2013) Analysis of genetic variability and genotype × year interactions on kernel zinc concentration in selected Indian and exotic maize (*Zea mays* L.) genotypes. Indian J Agric Sci 83:836–841
25. Gupta HS (2014) Enrichment of nutritional quality in maize through molecular breeding In: Proceedings of the national symposium on crop improvement for inclusive sustainable development. 07–09, November 2014, PAU, Ludhiana, p 7
26. Gupta HS, Babu R, Agrawal PK, Mahajan V, Hossain F, Nepolean T (2013) Accelerated development of quality protein maize hybrid through marker-assisted introgression of *opaque-2* allele. Plant Breed 132:77–82
27. Om Hari, Singh SP, Singh JK, Singh RN, Ansari MA, Meena RL, Yadav B (2014) Productivity, nitrogen balance and economics of winter maize (*Zea mays*) as influenced by QPM cultivars and nitrogen levels. Indian J Agric Sci 84:306–308
28. Harjes CE, Rocheford TR, Bai L, Brutnell TP, Kandianis CB, Sowinski SG, Stapleton AE, Vallabhaneni R, Williams M, Wurtzel ET, Yan J, Buckler ES (2008) Natural genetic variation in *lycopene epsilon cyclase* tapped for maize biofortification. Science 319:330–333
29. Hossain F, Nepolean T, Vishwakarma AK, Pandey N, Prasanna BM, Gupta HS (2013) Mapping and validation of microsatellite markers linked to *sugary1* and *shrunken2* genes in maize (*Zea mays* L.). J Plant Biochem Biotech. doi: 10.1007/s13562-013-0245-3
30. Hossain F, Prasanna BM, Sharma RK, Kumar P, Singh BB (2007) Evaluation of Quality Protein Maize (QPM) genotypes for resistance to stored grain weevil, *Sitophilus oryzae*. Int J Trop Insect Sci 27:114–121
31. Hossain F, Tripathi S, Warsi MZK (2004) Inter-character correlation and coefficient of variation in inbeds and their hybrids of maize grown under normal and water logged condition. Crop Res 27:270–274
32. Hossain F, Tripathi S, Warsi MZK (2004) Combining ability analysis in flood tolerant maize inbred lines and their hybrids under water logged situation. Crop Res 27:266–269
33. Intergovernmental Panel on Climate Change (2007) Climate change 2007: synthesis report. Cambridge University Press, Cambridge http://wwwipccch/pdf/assessmentreport/ar4/syr/ ar4_syrpdf
34. James C (2013) Global status of commercialized biotech/GM crops 2013 ISAAA brief no 46 ISAAA Ithaca, NY
35. Jat M, Satyanarayana T, Kaushik M, Parihar CM, Jat SL, Tetarwal J, Jat RK, Saharawat YS (2013) Fertilizer best management practices for maize systems. Indian J Fertil 9:80–94
36. Khanduri A, Hossain F, Lakhera PC, Prasanna BM (2011) Effect of harvest time on kernel sugar concentration in sweet corn. Indian J Genet Plant Breed 71:231–234
37. Khanduri A, Prasanna BM, Hossain F, Lakhera PC (2010) Genetic analyses and association studies of yield components and kernel sugar concentration in sweet corn. Indian J Genet Plant Breed 70:257–263
38. Khehra AS (1987) Cold tolerance of maize genotypes under different methods of sowing and plant densities. Crop Improv 14:92–94
39. Khehra AS, Dhillon BS (1984) Breeding maize for cultivation in winter. Punjab Agricultural University, Ludhiana
40. Kumar RS, Karjagi CG, Kumar B (2011) Improving the maize productivity in India: progress, challenges and opportunities. In: Zaidi et al (eds) Extended summaries of 11th Asian maize conference on 'addressing climate change effects and meeting maize demands for Asia' held at Nanning, China. 7–11, November 2011, pp 153–156
41. Lee EA, Staebler MA, Tollenaar M (2002) Genetic variation in physiological discriminators for cold tolerance—early autotrophic phase of maize development. Crop Sci 42:1919–1929
42. Mallikarjuna MG, Nepolean T, Hossain F, Manjaiah KM, Singh AM, Gupta HS (2014) Genetic variability and correlation of kernel micronutrient among exotic quality protein maize inbreds and their utility in breeding programme. Indian J Genet Plant Breed 74:166–173
43. Manivannan A, Kaul J, Singode A, Dass S (2010) Callus induction and regeneration of elite Indian maize inbreds. African. J Biotech 9:7446–7452
44. Mertz ET, Bates LS, Nelson OE (1964) Mutant gene mutant that changes the protein composition and increases the lysine content of maize endosperm. Science 145:279–280
45. Miedema P (1982) The effect of low temperature on *Zea mays*. Adv Agron 35:93–127
46. Mohammadi SA, Prasanna BM, Sudan C, Singh NN (2002) A microsatellite marker based study of chromosomal regions and gene effects on yield and yield components in maize. Cell Molec Biol Lett 7:599–606
47. Mondal TK, Ganie SA, Rana MK, Sharma TR (2013) Genome-wide analysis of zinc transporter genes of maize (*Zea mays*). Plant Mol Biol Rep 32:605–616
48. Mukherjee BK, Gupta NP, Singh SB, Singh NN (1971) Metroglyph analysis of Indian and exotic varieties of maize. Euphytica 20:113–118
49. Muthusamy V, Hossain F, Thirunavukkarasu N, Choudhary M, Saha S, Bhat JS, Prasanna BM, Gupta HS (2014) Development of β-carotene rich maize hybrids through marker-assisted introgression of *β-carotene hydroxylase* allele. PLOS One 9:e113583. doi:10.1371/journalpone0113583
50. Nair SK, Prasanna BM, Garg A, Rathore RS, Setty TAS, Singh NN (2005) Identification and validation of QTLs conferring resistance to sorghum downy mildew (*Peronosclerospora sorghi*) and Rajasthan downy mildew (*P heteropogoni*) in maize. Theor Appl Genet 110:1384–1392
51. Nsanzabaganwa E, Das TK, Rana DS, Kumar SN (2014) Nitrogen and phosphorus effects on winter maize in an irrigated agroecosystem in western Indo-Gangetic plains of India. Maydica 59:152–160
52. Payak MM, Sharma RC (1985) Maize diseases and approaches to their management in India. Trop Pest Manag 31:302–310
53. Prasanna BM (2010) Phenotypic and molecular diversity of maize landraces: characterization and utilization. Indian J Genet Plant Breed 70:315–327
54. Prasanna BM, Mazumdar S, Chakraborti M, Hossain F, Manjaiah KM, Agrawal PK, Gupta HS (2011) Genetic variability and genotype × environment interactions for kernel iron and zinc concentrations in maize (*Zea mays* L.) genotypes. Indian J Agric Sci 81:704–711
55. Prasanna BM, Pixley KV, Warburton M, Xie C (2010) Molecular marker-assisted breeding for maize improvement in Asia. Mol Breed 26:339–356
56. Prasanna BM, Chaikam V, Mahuku G (eds) (2012) Doubled haploid technology in maize breeding: theory and practice. D.F., CIMMYT, Mexico

57. Pushpavalli SNCVL, Sudan C, Singh NN, Prasanna BM (2001) Differentiation of elite Indian maize hybrids using simple sequence repeat markers. Indian J Genet Plant Breed 61:304–308
58. Rakshit S, Rashid Z, Sekhar JC, Fatma T, Dass S (2010) Callus induction and whole plant regeneration in elite Indian maize (*Zea mays* L.) inbreds. Plant Cell, Tissue Org Cul 100:31–37
59. Rakshit S, Santosh HB, Sekhar JC, Nath R, Meena S, Chikkappa GK, Gadag RN, Dass S (2011) Analysis of genetic diversity among maize inbred lines differing for resistance to pink borer and post-flowering stalk rot. J Plant Biochem Biotech 20:173–181
60. Rathore RS, Bohra B, Trivedi A, Mathur K (2005) An overview of fusarium stalk rot of maize in Rajasthan.In: Progress and future perspective in the 9th Asian regional maize workshop. 5–9, September 2005 Beijing, China, CAAS and CIMMYT Section-II Biotic and Abiotic stresses. pp 175–178
61. Sahu B (2006) Yield and economics of intercropping legumes in maize (Zea *mays)* under rainfed conditions. Indian J Agric Sci 76:554–556
62. Shanti K, Rao VP, Reddy MR, Reddy MS, Sarma PS (1997) Response of maize *(Zea mays)* hybrid and composite to different levels of nitrogen. Indian J Agric Sci 67:424–425
63. Sharma L, Prasanna BM, Ramesh B (2010) Analysis of phenotypic and microsatellite-based diversity of maize landraces in India, especially from the North East Himalayan region. Genetica 138:619–631
64. Singh B (1977) Races of maize in India. ICAR, New Delhi
65. Singh AK, Jat SL, Parihar CM (2014) Efficient nutrient, water and weed management in corn In: Rana et al (eds) Natural resource management for sustainable agriculture. Indian Agricultural Research Institute, New Delhi pp 268–274
66. Singh D (2010) Impact of scheduling nitrogen on productivity of single cross maize (*Zea mays*) hybrids. Indian J Agric Sci 80:649–651
67. Singh D, Sanghi SM (2006) Response of early maturing maize *(Zea mays)* hybrids to applied nutrients and plant densities under agroclimatic conditions of Udaipur in Rajasthan. Indian J Agric Sci 76:372–374
68. Singh I, Langyan S, Yadava P (2014) Sweet corn and corn-based sweeteners. Sugar Tech 16:144–149
69. Singode A, Prasanna BM (2010) Analysis of genetic diversity in the North Eastern Himalayan maize landraces using microsatellite markers. J Plant Biochem Biotech 19:33–41
70. Sivaranjani R, Prasanna BM, Hossain F, Santha IM (2013) Genetic variability for total carotenoid concentration in selected maize inbred lines. Indian J Agric Sci 83:431–436
71. Sivaranjani R, Santha IM, Pandey N, Vishwakarma AK, Nepolean T, Hossain F (2014) Microsatellite-based genetic diversity in selected exotic and indigenous maize (*Zea mays* L.) inbred lines differing in total kernel carotenoids. Indian J Genet Plant Breed 74:34–41
72. Soujanya PL, Sekhar JC, Kumar P (2013) Maize genotypes and resistance to rice weevils, *Sitophilus oryzae* (Coleoptera: Cuculionidae) and Angoumois grain moth, *Sitotroga cerealla* (Lepidoptera: Gelechidae). Indian J Entomol 75:157–162
73. Sureshkumar S, Tamilkumar P, Thangavelu AU, Senthil N, Nagarajan P, Vellaikumar S, Ganesan KN, Balagopal R, Ravindran M (2014) Marker-assisted introgression of *lpa-2* locus responsible for low-phytic acid trait into an elite tropical maize inbred. Plant Breed 133:566–578
74. Tamilkumar P, Senthil N, Sureshkumar S, Thangavelu AU, Nagarajan P, Vellaikumar S, Ganesan KN, Natarajan N, Balagopal R, Nepolean T, Raveendran M (2014) Introgression of low phytic acid locus *(lpa2-2)* into an elite Maize (*Zea mays* L.) inbred through marker assisted backcross breeding. Aust J Crop Sci 8:1224–1231
75. Thirunavukkarasu N, Hossain F, Shiriga K, Mittal S, Arora K, Rathore A, Mohan S, Shah T, Sharma R, Namratha PM, Mithra ASV, Mohapatra T, Gupta HS (2013) Unraveling the genetic architecture of subtropical maize (*Zea mays* L.) lines to assess their utility in breeding programs. BMC Genom 15:1182
76. Thirunavukkarasu N, Hossain F, Mohan S, Shiriga K, Mittal S, Sharma R, Singh RK, Gupta HS (2013) Genome-wide expression of transcriptomes and their co-expression pattern in subtropical maize (*Zea mays* L.) under waterlogging stress. PLOS One 8(e70433):1–12
77. Timsina J, Jat ML, Majumdar K (2010) Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. Plant Soil 335:65–82
78. Tiwari A, Prasanna BM, Hossain F, Guruprasad KN (2012) Analysis of genetic variability for kernel carotenoid concentration in selected maize inbred lines. Indian J Genet Plant Breed 72:1–6
79. Tripathi S, Warsi MZK, Verma SS (2003) Water logging tolerance in inbred lines of maize (*Zea mays* L.). Cereal Res Commun 31:221–226
80. Vasal SK (2000) The quality protein maize story. Food Nutr Bull 21:445–450
81. Vignesh M, Hossain F, Nepolean T, Saha S, Agrawal PK, Guleria SK, Gupta HS (2015) Genetic variability and inter-relationship of kernel carotenoids among indigenous and exotic maize (*Zea mays* L.) inbreds. Cereal Res Commun. doi:10.1556/0806.43.2015.012
82. Vignesh M, Hossain F, Nepolean T, Saha S, Agrawal PK, Guleria SK, Prasanna BM, Gupta HS (2012) Genetic variability for kernel β-carotene and utilization of *crtRB1* 3′TE gene for biofortification in maize (*Zea mays* L.). Indian J Genet Plant Breed 72:189–194
83. Wasala S, Prasanna BM (2013) Microsatellite marker-based diversity and population genetic analysis of selected lowland and mid-altitude maize landrace accessions of India. J Plant Biochem Biotech 22:392–400
84. Yadav OP, Karjagi CG, Jat SL, Dhillon BS (2014) Overview of maize improvement in India. Indian Farm 64:5–11
85. Yan J, Kandianis BC, Harjes EC, Bai L, Kim HE, Yang X, Skinner DJ, Fu Z, Mitchell S, Li Q, Fernandez GSM, Zaharoeva M, Babu R, Fu Y, Palacios N, Li J, DellaPenna D, Brutnell T, Buckler SE, Warburton LM, Rocheford T (2010) Rare genetic variation at *Zea mays crtRB1* increases beta carotene in maize grain. Nat Genet 42:322–327
86. Yang W, Zheng Y, Zheng W, Feng R (2005) Molecular genetic mapping of a high-lysine mutant gene (*opaque-16*) and the double recessive effect with *opaque-2* in maize. Mol Breed 15:257–269
87. Zaidi PH, Maniselvan P, Sultana R, Chauhan S, Singh RP, Singh N, Srinivasan G (2005) Drought tolerance in tropical maize—problems and prospects. In: Zaidi PH, Singh NN (eds) Stresses on maize in tropics. Directorate of Maize Research, New Delhi, pp 67–99
88. Zaidi PH, Maniselvan P, Rafique S, Yadav P, Singh RP, Srinivasan G (2007) Importance of secondary traits in improvement of maize (*Zea mays* L.) for improving tolerance to excessive soil moisture stress. Cereal Res Commun 35:1427–1435
89. Zaidi PH, Singh NN (2005) Maize in tropics—phenology and physiology. Directorate of Maize Research, New Delhi, pp 56–64
90. Zaidi PH, Maniselvan P, Yadav P, Singh AK, Rizvi R, Dureja P, Singh NN, Srinivasan G (2007) Stress-adaptive changes in tropical maize (*Zea mays* L.) under excessive soil moisture stress. Maydica 52:159–173
91. Zaidi PH, Maniselvan P, Rizvi R, Srivastava A, Singh RP, Singh NN, Srinivasan G (2007) Association between line *per se* and hybrid performance under excessive soil moisture stress in tropical maize (*Zea mays* L.). Field Crop Res 101:117–126

92. Zaidi PH, Maniselvan P, Srivastava A, Yadav P, Singh R (2010) Genetic analysis of waterlogging tolerance in tropical maize. Maydica 55:17–26
93. Zaidi PH, Rafique S, Singh NN (2003) Response of maize (*Zea mays* L.) genotypes to excess moisture stress: morpho-physiological effects and basis of tolerance. Eur J Agron 19:383–399
94. Zaidi PH, Rafique S, Rai PK, Singh NN, Srinivasan G (2004) Tolerance to excess moisture in maize (*Zea mays* L.): susceptible crop stages and identification of tolerant genotypes. Field Crop Res 90:189–202
95. Zaidi PH, Yadav M, Maniselvan P, Khan R, Shadakshari TV, Singh RP, Pal D (2010) Morpho-physiological traits associated with cold tolerance in tropical maize (*Zea mays* L.). Maydica 55:201–208