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CHILLI (*Capsicum annuum* L.) BREEDING IN INDIA: AN OVERVIEW

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SUMMARY

Chilli (*Capsicum annuum*) is an important commercial and export-oriented crop in India. In this paper, an overview of chilli breeding research in India has been given.Germplasm sources resistant to *Chili/pepper leaf curl virus* (ChiLCV) *Chili veinal mottle virus* (ChiMoV), *Cucumber mosaic virus* (CMV), anthracnose, bacterial wilt, nematodes and powdery mildew have been identified and used in current breeding programs. The northeast region has emerged as having a novel diversity in the cultivated species of the genus *Capsicum.* Nuclear and cytoplasmic male sterility system have been developed and exploited at commercial scale to develop hybrids and their seeds. The developmental accomplishments including national releases of commercial chilli cultivars (open pollinated varieties and hybrids) and dissemination of their seed has been discussed. Changes in climate and society are explored as they relate to chilli production; research across multiple sectors is advocated to address these and other concerns to boost the chilli industry.

Keywords: Genetic resources, hybrid, male sterility, resistance breeding, pepper

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INTRODUCTION

Chilli (*Capsicum* spp.) is an important commercial spice and vegetable crop for small and marginal farmers in Asia, Africa and South America. Among the 5 cultivated species of the genus *Capsicum*, *C. annuum* is the most widely cultivated in India for its pungent (chilli syn. hot pepper) and non-pungent (sweet pepper syn. capsicum, bell pepper) fruits. The cultivation of *C. frutescens*, *C. chinense*, and *C. baccatum* is limited and usually restricted to homestead gardening in different regions.

According to an estimate for 2012, in India, chillies (dry-red and fresh-green fruits) were cultivated on 801,500 ha with a total production of 1.3 million t of dry fruits and 6800 t of fresh fruits. Average yield of dry chilli harvest was around 1.6 t/ha compared to those of 8.5 t/ha for green chilli (FAOSTAT, 2012). In India, the states of Andhra Pradesh, Karnataka, Maharashtra, Orissa and Tamil Nadu account for more than 75% of the area and total production of chilli.

Pepper (chilli and sweet) market types prevalent in India can broadly be grouped into

the following 4 categories: (i) fresh market (green, red, multi-color whole fruits), (ii) fresh processing (sauce, paste, canning, pickling), (iii) dried spice (whole fruits and powder), and (iv) industrial extracts (paprika oleoresin, capsaicinoids and carotenoids). Besides conventional nutritional food uses, a number of versatile food (paprika oleoresin) and non-food (defense, spiritual, ethnobotanical) uses of chillies are known (Kumar *et al.,* 2006a; Meghavansi *et al.,* 2010). Among the exported spices from India, export of dry chilli and its derived products (Figure 1) stand first in terms of quantity and second in terms of total value after mints (menthol, menthol crystal and mint oils). Malaysia is the largest importer of Indian chilli (~30%), followed by other traditional importers like Bangladesh (~20%), Sri Lanka (15%), USA (9%), and UAE (8%). These figures do not include fresh chilli exports and chilli oleoresin, which constitutes a major share of spice oleoresins exported from India.

In the post-Mendelian era of crop improvement, systematic chilli breeding research in India started in the 1930s with efforts to understand inheritance of important traits such as pungency (Deshpande, 1933; 1935; Ramaiah and Royappa, 1935). In 1971, the establishment of All-India Coordinated Research Project (AICRP) on Vegetables at Indian Agricultural Research Institute (IARI), New Delhi paved the way for research coordination and multilocation evaluation of chilli cultivars. Public sector institutions are mostly involved in strategic research to develop improved varieties with limited dissemination efforts on seed multiplication, while private seed companies are mostly involved in development, promotion and commercialization of hybrid cultivars.

This paper provides status and the progress of chilli breeding research in India along with future needs concerning *Capsicum* germplasm conservation and chilli improvement.

CAPSICUM DIVERSITY AND CHARACTERIZATION

The National Bureau of Plant Genetic Resources (NBPGR), New Delhi facilitates collection, regeneration, characterization, conservation and distribution of chilli germplasm to researchers in India. However, at NBPGR indigenous collections constitute only 18% of the total *Capsicum* collections, while the majority of the accessions (2412) are exotics (Kalloo *et al.,* 2005). The NBPGR currently has ~3000 *Capsicum* accessions under *ex situ* conservation, but online passport and characterization data are not available.

Phylogenic analysis based on seed protein has revealed that *C. annuum* accessions from Kerala might have been introduced from Portugal (Anu and Peter, 2003). Random amplified polymorphic DNA (RAPD) based cluster analysis of 7 chilli landraces from Manipur separated *C. annuum* genotypes (1 cluster) from *C. frutescens* and *C. chinense* (another cluster). Genetic variation among *C. annuum* genotypes was higher compared with *C. frutescents* genotypes and *C. chinense* genotypes, most of which were closely related (Sanatombi *et al.,* 2010).

Discovery of novel genetic resources

The northeast region consisting of states like Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura is recognized as hot-spot for chilli diversity. During the last decade, *Capsicum* landraces from this region have received renewed attention due to the discovery of India's hottest chilli (Naga Jolokia) from Assam (Mathur *et al.,* 2000). Later, a variant of this landrace (Bhut Jolokia) was reported as world's hottest with possible origin through natural crossing between *C. chinense* and *C. frutescens* (Bosland and Baral, 2007). A number of variants of these landraces probably derived from natural inter-specific crosses are known in the region (Kumar *et al.,* 2011) under different local names (Sanatombi *et al.,* 2010; Verma *et al.,* 2013). In general, these landraces have highly pungent fruits (Sanatombi *et al.,* 2010) and are potential sources of capsaicinoids with broad-spectrum ethno-pharmaceutical uses (Meghvansi *et al.,* 2010). Landraces like BS35, GKC29 and Bhut Jolokia are resistant to *Pepper leaf curl virus*-Varanasi strain (Kumar *et al.,* 2006b, Table 1) and Naga Chilli is susceptible to *Chilli veinal mottle virus*

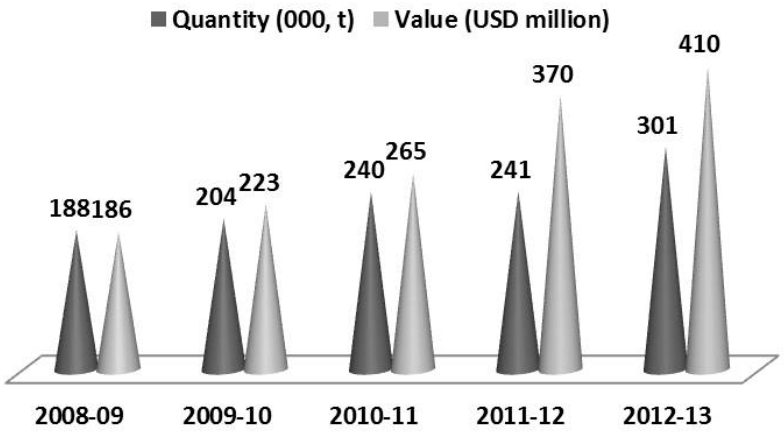

Figure 1. Export trends of dry chilli and its derived products from India.

Table 1. Identified resistant/tolerant source against major pests of chilli in India, since 2000.

Biotic stress and *causal organism*		Name of line and reference
Anthracnose (*Colletotrichum* spp.)	:	Bhut Jolokia (Gerg *et al.,* 2013); PBC80 (VI046804), PBC81 (VI046805), PBC932 (VI047018); LLS, Breck-1, Breck-2, Jaun (Kaur *et al.,* 2011)
Bacterial wilt (*Psedomonas solanacearum*)	:	AVPP0102 (PP0107-7011), PBC66 (VI037518), PBC67 (VI037519), PBC384 (VI037548), PBC385 (VI039374), PBC535 (VI037556), MC-4
Phytophthora blight (*Phytophthora capsici)*	:	GKC29, PI201234, IC364063
Chili/pepper leaf curl virus (ChiLCV)	:	BS35, GKC29, Bhut Jolokia (Kumar *et al.,* 2006b; Kumar *et al.,* 2011), CHUH-4 (Mondal, 2013), Pepper Line Nos. 59 & 86
Chili veinal mottle virus (ChiMoV)	:	Individual plant selections from: PBC495 (VI037455), PBC521, PBC370 (VI037453), PBC569 (VI046889), PBC371 (VI039369), Tiwari (Erect), 9852-131 (AVPP9807), Punjab Gucchedar, Perennial, Punjab Surkh, Pusa Sadabahar, Pant C1, Perennial HDV (Reddy and Reddy, 2010)
Cucumber mosaic virus (CMV)	:	Perennial, PBC495 (VI037455), VC246, VR42, VR55 (Reddy and Reddy, 2010), AVPP9812 (PP9852-10)
Peanut bud necrosis virus (PBNV)	:	EC121490, IC119611 (Kalloo *et al.,* 2005)
Nematode (*Meloidogyne javanica)*	:	EC402105, EC402113, EC405253, NIC19969, IC214965, IC214985, IC215012, EC391083, EC391087, EC378632, EC378688 (Pandravada *et al.,* 2010)
Powdery mildew (*Leveillulataurica*)	:	Arka Harita, Arka Suphal, PBC167 (VI046819)
Thrips	:	Caleapin Red, Chamatkar, P46-A, X1068, X743, X1047, BG4, X226, X230, X233 (Kalloo *et al.,* 2005)
Yellow mites (*Polypagotarsonemus latus*)	:	Jwala, RHRC Erect, AEG77 (Desai *et al.,* 2007)

(Banerjee *et al.,* 2014). Distinctness of variants of Bhut Jolokia from *C. frutescens* and *C. chinense* has been demonstrated by phylogenetic analysis based on ribosomal RNA (rRNA) gene-internal transcribed (ITS) region sequences (Purkayastha *et al.,* 2012a). The existence of unique diversity in the region has been further strengthened with the discovery of a naturally occurring allotetraploid chilli in the region (Jha *et al.,* 2012).

In a molecular marker diversity analysis, the landraces from the northeast region clustered with non-*annuum* (*i.e. C. frutescens, C. chinense, C. baccatum*) genotypes (Rai *et al.,* 2013). Crossing attempts involving 3 of these landraces to *C. annuum* revealed that they were reproductively isolated (pre-hybridization barrier and post-hybridization barrier of hybrid breakdown) from *C. annuum* genotypes (Rai *et al.,* 2014) and are believed to have originated from sympatric domesticated species rather than introduction from elsewhere (Rai *et al.,* 2013). This hypothesis (origin of landraces from natural crossing between sympatric populations) is further strengthened by the results of an independent study involving diversity analysis of 53 landraces collected from the north east region of India (Yumnam *et al.,* 2012). The study revealed (i) the presence of novel single nucleotide polymorphisms (SNPs) across *Pun1* locus and (ii) that out of the total variation, 58% of the variation occurred among plants within populations and 34% among populations within the same group. This points to possible gene-flow among populations in the recent past and indicates that populations have not been isolated from each other long enough (Yumnam *et al.,* 2012). It seems that these landraces have not yet reached the species differentiation level; it is premature to propose them as separate species (Verma *et al.,* 2013) in contrast to a proposal to treat some of these landraces from Assam as a separate sixth domesticated species (*C. assamicum*) by Purkayastha *et al.* (2012b).

Genetic resources against biotic stresses

Commercial chilli production is adversely affected by attack of insect-pests and diseases. Host plant resistance is generally considered a cost-effective and safe method of controlling insect pests with regard to the environment and health of producers and consumers. A detailed account of global sources of resistance to major chilli pests and diseases, including those reported from India was given by Babu *et al.* (2011).

CHARACTERIZATION OF CHILLI PATHOGENS

Understanding of prevalent species and the pathotype/biotype or strain of a given pathogen in the targeted production region is crucial for breeding resistant cultivars.

***Colletotrichum* spp.**

Different species of *Colletotrichum*, *viz.*, *C. capsici*, *C. gloeosporioides* and *C. acutatum* are known to cause anthracnose disease of chilli in India and many other countries in Southeast Asia and Oceania. *Colletotrichum capsici* and *C. gloeosporioides* were the 2 predominant species in Southern India (Rao *et al.,* 2007). *C. capsici* was prominent in Karnataka, Tamil Nadu and Maharashtra (Rao *et al.,* 2007), Himanchal Pradesh (Sharma *et al.,* 2005), Andhra Pradesh (Rao *et al.,* 2007; Pratibha, 2009; Nanda, 2011) and in Arunachal Pradesh (Selvakumar, 2007). Isolates have been characterized based on mycelium and conidia morphology (Pratibha, 2009), conidial shape, internal transcribed spacer (ITS) of ribosomal DNA and amplified length polymorphism (AFLP) markers (Nanda, 2011), level of aggressiveness (Sharma *et al.,* 2005), differential reactions against given host genotypes (Khirbhat *et al.,* 2004; Deshpande and Rawal, 2007; Garg *et al.,* 2013). Recently, a real time polymerase chain reaction (PCR) protocol for specific and efficient detection of *C. capsici* has been reported (Srinivasan *et al.,* 2014).

Viruses

More than 20 viruses are known to infect chilli and sweet peppers in India. Among these, *Chilli veinal mottle virus* (ChiVMV) of the *Potyvirus* genus, *Cucumber mosaic virus* (CMV) of the *Cucumovirus* genus, chilli infecting begomovirus causing leaf curl diseases (referred here as *Chili leaf curl virus*, ChiLCV) and *Groundnut bud necrosis virus* (GBNV) or *Peanut bud necrosis virus* (PBNV) of the *Tospovirus* genus are currently considered to be the most important (Reddy and Reddy, 2010).

ChiVMV is transmitted by aphids in a non-persistent manner and is the most prevalent potyvirus in India. Isolates of ChiVMV were identified from Karnataka and Tamil Nadu based on host range, serological relationship, electron microscopy and phylogenetic analysis of coat protein sequences. Nucleotide sequence analysis of these isolates revealed > 90% similarity with already known ChiVMV sequences. Symptom variation and severity also varied among the ChiVMV isolates (Reddy and Reddy, 2010).

CMV is transmitted mainly by aphid species in a non-persistent manner. Host range, electron microscopy and partial molecular characterization studies have confirmed CMV incidence and distribution on chilli from the northern Telengana region of Andhra Pradesh (Reddy and Reddy, 2010).

ChiLCV transmitted by whitefly has emerged as a serious problem throughout India. *Tomato leaf curl Joydebpur virus* (reported earlier from tomato in Joydebpur, Bangladesh) has also been found to be associated with chilli leaf curl disease in Punjab (Shih *et al.,* 2006). A complete begomovirus sequence associated with chilli leaf curl disease from Varanasi, Uttar Pradesh shared ~95% sequence identity with ChiLCV-PK and infectivity of the cloned molecule was demonstrated in the natural host for the first time (Chattopadhyay *et al.,* 2008). Complete sequencing of DNA-A from different samples indicates association of 3 distinct begomoviruses with this disease. An isolate from Kalyani (West Bengal) shared maximum nucleotide identity with *Pepper leaf curl Bangladesh virus* (96.3%) while 3 isolates from Rajasthan showed nucleotide identity of 88.9 to 91.1% with *Chilli leaf curl virus*-Multan, and 8 isolates (2 each from Delhi, Haryana, Punjab and Uttar Pradesh) shared nucleotide identity of 92.4 to 98.5% with *Tomato leaf curl New Delhi virus* (Reddy and Reddy, 2010). Based on *cp* sequence analysis, emergence of new variants of ChiLCV has been reported (Rai *et al.,* 2010). For the first time, the virus-vector relationships and host range of ChiLCV isolate from Rajasthan have been described (Senanayake *et al.,* 2012). The beta-satellite of this virus was resembled most closely (97.3%) with Tomato leaf curl Bangladesh beta-satellite previously reported from chilli and tomato in India (Senanayake *et al.,* 2012).

In recent years, tospoviruses (PBNV/GBNV) transmitted by thrips have emerged as a major threat for chilli cultivation in India. Tospovirus, (PBNV) was widely recorded on tomato and chili peppers across 14 Indian states representing southern, northwestern, northeastern and central regions (Kunkalikar *et al.,* 2011).

CYTOGENETICS

In situ nuclear DNA contents varied significantly between 23 *C. annuum* genotypes with somatic chromosome number 2*n* = 24 (Mukherjee and Sharma, 1990). *Capsicum* cytogenetic analyses in India were carried out by a few groups, especially by Aneil Kumar O and his associates at Andhra University, Vishakhapatnam. During the 1980s they studied meiotic behavior of cytogenetic stocks such as accidentally induced interchange (Rao and Kumar, 1983), induced octaploid (Panda *et al.,* 1984) and inter-specific crosses (Kumar *et al.,* 1987; 1988). Besides some minor chromosome structural differences, the *C. annuum* accession used differed from *C. chinense* by 2 translocations and from *C. baccatum* accession by 2 translocations and 1 inversion (Kumar *et al.,* 1987). In the past decade, progress has been limited to meiotic analysis of male sterile lines (Dash *et al.,* 2001; Kumar *et al.,* 2001), study on meiotic consequences of chromosomal aberrations (Dhamayanthi and Reddy, 2000), meiotic analysis to determine chromosome number and structure in the process of polyploid induction (Ranganathan and Jagatheeshwari, 2013), and to study meiotic behavior and karyotype of an allotetraploid (Jha *et al.,* 2012).

TISSUE CULTURE AND TRANSGENICS

Peppers (chilli and sweet pepper), unlike tomato, tobacco and petunia have an inherent problem associated with *in vitro* regeneration. The severe recalcitrant morphogenic nature of peppers, formation of rosette shoots and ill-defined shoot buds and genotypic dependent tissue culture response in peppers (Kothari *et al.,* 2010) have hampered progress in tissue culture advancements and genetic transformation of chilli. Progress on transformation of *Capsicum*

Table 2. Reports on transformation of *Capsicum* in India (since 2000).

Genotype; transformation method	Vector, reporter gene/s (selection agents)	Remarks	Reference
Pusa Jwala; *Agrobacterium* (C58)	pGV1040:: *phosphotransferase-II* (*nptII*) + *β-glucuronidase* (*gus*) (kanamycin and cefotaxime)	The transformed shoots were selected, rooted and transgene presence was confirmed through GUS assay, PCR and southern blotting of *nptII*	Shivegowda *et al.* (2002)
K1, K2, PLR1; *Agrobacterium* (EHA 105)	T-DNA with CaMV 35S::*gus* (cefotaxime and anamycin)	The integration of *gus* gene in genome was confirmed by histochemical *gus* staining, PCR and southern analysis	Sobhakumari and Lalithakumari (2005)
Byadagi Kaddi, *Agrobacterium* (EHA105)	pBinBt3::*cryI(Ac)* + *nptII* under *CaMV35S* promoter and *nos* terminator (kanamycin)	Pre-cultured explants were more suitable for transformation. 0.5×10^8 bacterial cells/ml was optimum for transformation	Channappagoudar (2007)
C. frutescens; Pollen transformation; *Agrobacterium* (EHA 101)	pCAMBIA::hygromycin phosphotransferase (*hpt II*) under CaMV *35S* promoter and terminator + β-glucuronidase (*uid* A) under CaMV *35S* promoter and *NOS* terminator (kanamycin)	Successful transformation of pollen from *in vitro* flowers induced through application of silver nitrate ($AgNO_3$) and cobalt chloride ($CoCl_2$)	Sharma *et al.* (2008)
Arka Gaurav, Arka Mohini; *Agrobacteriumin planta* (EHA105)	pCAMBIA1301:: β-glucuronidase (*uid A*) + *hptII* reporters; (kanamycin)	Genotype independent protocol for *in planta* transformation of sweet pepper, identified stable transformants based on PCR analysis	Kumar *et al.* (2009)
California Wonder; *Agrobacterium* (LBA 4404)	pBI121::*npt*-II + *gus* reporters (cefotaxime and kanamycin)	Standardization of pre-culture and co-cultivation time	Verma *et al.* (2013)
Pusa Jwala *Agrobacterium* (EHA105)	pBinARβC1::*nptII* + *βC1* (kanamycin and rifampicin)	Transgenic plants with *βC1* gene (satellite DNA β molecule of *chilli leaf curl virus*, useful in understanding *βC1*-mediated pathogenesis	Kumar *et al.* (2012)
Sweet pepper; *In planta Agrobacterium*	Pathogenesis-related gene (*NPR1*) for resistance to powdery mildew	Technology can be used as a versatile tool in economically important crop species	Arthikala *et al.* (2014)

spp. in India is summarized in Table 2. Parthasarathy *et al.* (2010) and Kothari *et al.* (2010) have reviewed *Capsicum* biotechnology. Recently, embryo rescue was successfully attempted to bypass pre-zygotic barriers in inter-specific crosses (Debbarama *et al.,* 2013). Research attempts to examine the potential of capsaicinoids synthesis under *in-vitro* culture by chilli pepper cells, tissues and organs has been also made (Kehie *et al.,* 2014).

MOLECULAR MARKERS

In *Capsicum*, markers have been used to tag desirable traits including QTLs (Ramchiary *et al.,* 2013). However, the in-past progress of marker development and its application in marker-assisted selection in chilli has been slow due the larger genome size of chilli and non-availability of the complete pepper genome sequence till

recently. Now pepper genome sequences have become available (Kim *et al.,* 2014; Qin *et al.,* 2014), which will substantially accelerate the process of markers application in chilli breeding. In India, markers have mostly been used for *Capsicum* germplasm diversity analysis and DNA fingerprinting of varieties (Singh *et al.,* 2008). The IIHR has completed marker based fingerprinting of all its released OPVs and inbreds of hybrids and at IIVR attempts were made to validate RAPD marker associated with *Rf* gene (Kumar *et al.,* 2007). Marker validation and utilization for screening CMS trait has been demonstrated (Kumar *et al.,* 2009). Morphological (floral characteristics) and molecular markers have been demonstrated to be useful for delineation of species specificity and identification of genetic stocks (Thul *et al.,* 2012). Cleaved amplified polymorphism (CAPS) analysis of populations derived from ChiVMV-resistant Perennial indicated that resistance was tightly linked with *pvr1*$_1$ locus on chromosome 4. Further, comparison of nucleotide sequence of the coding region indicated 99.1 to 99.5% protein and 99.1 to 99.8% nucleotide identity with genotype carrying *pvr11* gene of the eukaryotic translation initiation factor *elF4E* family (Reddy and Reddy, 2010). Ten QTLs for yield-related traits were mapped on 4 linkage groups (LG) out of which 9 were stable. The phenotypic contribution of these QTLs ranged from 8 to 51% (Dwivedi *et al.,* 2013).

VARIETAL DEVELOPMENT

Considerable progress has been made on the development, release and commercialization ofchilli cultivars in India. In India, the chilli varietal release procedure is facilitated by All India Co-ordinated Research Project (AICRP) on vegetable crops (responsible for coordination of multi-location evaluation and recommendation of better performing OPVs or hybrids for release and cultivation) and the Central Variety Release Committee (CVRC) on Horticultural Crops (responsible for official release notification of cultivars). In addition, different state governments also release or notify varieties through State Varietal Release Committees (SVRCs) in respective states. According to the Protection of Plant Variety and Farmers Right Act (PPV&FR Act 2001), it is up to the breeder, farmer or institution to decide to register notified cultivars with the PPV&FR authority (responsible for executing PPV&FR). If a plant breeder (a person or group of persons, a farmer or group of farmers, or an institute as defined in the PPV&FR Act) wish to protect the cultivar, it must go through a distinctiveness, uniformity and stability (DUS) test implemented by ICAR on behalf of the PPV&FR authority.

Table 3. List of chilli cultivars recommended for national release in India (1975-2014).

Cultivar type (developed by)		Name (recommended zone/s)
Open pollinated (all 24 by public sector)	:	G-4 or Bhagyalakshmi, G-5 or Andra Jyothi (I, IV, V, VI, VII, VIII), K-2 (IV, VI), J-218 (I, IV, V, VI, VII), Bhaskar or X-235 (IV, V, VI, VIII), Muslawadi (V), Arka Lohit/Sel-1 (V, VII, VIII), LCA206-B (V, VI, VII, VIII), Phule C-5(VII), AKC-86-39 (VII), BC-14-2 (V, VI), RHRC-Cluster Erect (VII), PMR57/88-K (VII), LCA-334 (III, IV, V, VII), ASC-2000-02 (VII), KA-2 or Kashi Anmol (IV), LCA-353 (IV, V, VII),BC-25 (V, VI, VII), PC-7 (V), HS-HP-154 (VIII), IVPBC-535 or Kashi Sinduri-Paprika (VIII), PC-56 (I, IV, V, VII, VIII), VR-338 (II), ACS-06-2 (VIII)
Hybrid (10 by private and 5 by public sector)	:	HOE-888 (IV, VIII), ARCH-236 (IV), Sungrow-86-235 (IV, VIII), ARCH-228 (IV, V, VI), Arka Meghana or MSH-172 (IV, V, VI & VIII), Arka Sweta or MSH-149 (IV, VI, VIII), CCH-2 or Kashi Surkh (II, IV, V, VI), KCH-3 (IV), CCH-3 or Kashi Early (IV, V, VIII), BSS-453 (II), NCH-587 (IV, VII), VNR-332 or Rani (IV, VIII), HH-41786 (VII), BSS-378 (VII), VNR-Vidya (IV)

Zones: I = Humid western Himalayan region, II =Humid Bengal-Assam basin, III = Humid eastern Himalyan and bay islands, IV = Sub-humid Satlej Ganga Alluvial plains, V = Sub-humid eastern and south eastern plains, VI = Arid western plains, VII = Semiarid plateau and central highlands, VIII = Humid, semi-arid Western Ghats and Karnataka plateau.

Since its inception in 1971, AICRP has recommended 24 open pollinated varieties (OPVs) and 15 hybrid chilli cultivars through multi-location evaluations for different agro-climatic zones (Table 3).

The Central Variety Release Committee (CVRC) has notified 57 chilli cultivars including 7 hybrids (notified after 2005) for cultivation in different zones. In the beginning, centers like the Regional Research Center, Lam, Andhra Pradesh were pioneers in developing and releasing several popular chilli cultivars (e.g., G-4, G-5, Sindur, etc.). Likewise Pusa Jwala released by IARI was very popular (Tiwari and Ramanujam, 1974) and now became a well-recognized market segment (pod type) in the pepper seed industry worldwide.

SEED DISSEMINATION BY PUBLIC INSTITUTIONS

Most of the improved chilli seeds in India are marketed by private seed companies through their own distribution networks. Seed dissemination efforts by public institutions are limited and are performed by ICAR institutes, SAUs and their extension wings, such as Krishi Vigyan Kendra (KVKs), and the Agriculture Information Technology Centers (ATIC). Public sector institutions are responsible for the breeder seed production of released OPVs and parents of hybrids. The National Seed Corporation (NSC) and the National Horticulture Research and Development Foundation (NHRDF) also undertake seed production of chilli cultivars. Multi-location evaluations of improved cultivars under AICRP provide opportunities to exchange improved seeds between the participating public and private sector stakeholders/members across the country. In addition, different research institutions and universities adopt their own strategies to disseminate improved seeds through public and private breeders to harness larger impact of their breeding research products. In the past decade, IIHR adopted impressive approaches to disseminate improved chilli and other vegetables. The institute has made its improved seeds available to interested public sector undertakings (e.g. NSC and NHRDF) and more than 20 private-sector seed companies. These institutions use IIHR-developed elite lines (e.g., disease-resistant and male sterile lines) and commercialized hybrids. Examples are described in the sections below.

COST-EFFECTIVE HYBRIDS USING MALE STERILITY

Male sterility systems are widely used to produce cost-effective hybrids and their seeds. In India, both nuclear male sterility (GMS) and cytoplasmic male sterility (CMS) systems have been developed and characterized in chilli and are being used for the development of experimental crosses, potential hybrids and production of hybrid seeds. It is expected that use of male sterility system in chilli would facilitate to reduce the cost of producing hybrids seeds by 40% (Lin *et al.*, 2013).

Nuclear/genic male sterility (GMS)

MS-12, a monogenic, recessive gms line, has been developed and commercially exploited in India. Thanks to pioneer efforts at Punjab Agricultural University (PAU), Ludhiana, where 2 hybrids (CH-2, CH-3) based on MS-12 were developed, farmers were trained to produce hybrid seed and were provided with male sterile female parents (MS-12) and male parents. This resulted in the adoption of hybrid seed production and hybrid production technologies by farmers in Punjab (Dhaliwal, 2010). Seed producers also market hybrid seeds in nearby regions of Uttar Pradesh, Haryana, and Rajasthan states. Since MS-12 line possess *ms-10* mutatnt gene induced through mutagenensis in France, the commercial exploitation of MS-12 is a classic example of indirect use of mutagenesis in crop improvement and PAU continue to use *ms-10* gene-based GMS line in heterosis breeding program (Singh *et al.,* 2014)

Cytoplasmic male sterility (CMS)

The area under chilli hybrid production in India has increased from 2.4% in 1997-1998 to about 25% at present. Recognizing the role of CMS lines in labor-saving, cost-effective hybrid seed production, IIHR developed 4 pairs of CMS and maintainer lines from a locally isolated male sterile cytoplasm (Reddy *et al.*, 2002). The male sterile cytoplasm was genetically similar to the most widely used Petersons cytoplasm (Kumar *et al.*, 2009). CMS lines were used to develop a

number of experimental crosses. Based on promising performance (yield and quality attributes), 4 hybrids (Arka Meghana, Arka Harita, Arka Sweta and Arka Kyathi) were identified for further promotion through different approaches.

More than dozen private seed companies have acquired CMS lines developed by IIHR and used them in commercial hybrid development and seed production. Eight seed companies acquired parents of hybrids and directly commercialized them. The exact area under commercial hybrid production by all seed companies is not known. Since 2010, government sector undertakings such as NSC and NHRDF also started producing hybrid seeds by engaging small seed producers with backstopping support from IIHR scientists. According to an estimate (based on amount of hybrid seeds produced and made available to the farmers by the NSC), Arka Meghna and Arka Harita were grown on about 2500 and 1500 ha, respectively in 2012. Recently, PAU has developed numerous potential crosses based on CMS line introduced from AVRDC (Singh *et al.*, 2014).

INDIAN PEPPER SEED INDUSTRY

Thanks to the post-liberalized Indian seed policy (after the late 1980s), the Indian private seed industry exploded, showing ~250% increase in R&D expenditures in 1997, compared to 1987. The financial investment was equally matched with other measures (capital investments, technical staff, size of experiment stations, etc.). The R&D efforts of the seed industry tripled within 8 years (Pray, 2001). Currently, there are ~850 small to large-sized seed companies operating in India, of which about 50 of them match with world-class, competitive human and infrastructural resources. Chilli hybrids and improved open-pollinated each contribute to ~25% of the total area under chilli cultivation; the remaining 50% area is still under local landraces. Owing to low volume and high cost of hybrid chilli seeds, scope for an increase in hybrid seed demand, both in India as well as for export of hybrid seeds, most seed companies have chilli hybrid development in their research and marketing portfolio. The current chilli hybrid seed market in India is ~50 tons per year, with an estimated turnover worth 16 m $. These figures do not include seeds of hot pepper OPVs or sweet pepper OPVs and hybrids.

PRESENT PROGRESS AND OUTLOOK

In the current scenario of developmental efforts being undertaken in northeast India, a regional *Capsicum* specific exploration that recognizes the role of local communities for *in situ* conservation should be conducted before important genetic resources get replaced by commercial cultivars due to profitable intensification.

Frequent and simultaneous occurrences of pests are a major constraint for commercial chilli production in India. Continued emergence of new pathogen races and strains against available resistant cultivars necessitates the search and use of new resistant sources. Following breeding progresses are underway at various institutions:

- The identified resistant sources to leaf curl virus are used to transfer resistance into desirable breeding lines. Progress is underway to study the genetics of resistance to the leaf curl complex causing begomovirus and to identify genes involved in plant defense against the leaf curl complex.
- Combining resistance to ChiVMV, CMV and thrips.
- Gene expression studies, development of functional markers and QTL mapping for anthracnose disease resistance.
- Diversification of CMS lines and incorporation of ChiVMV and *Phytophthora* root rot resistance into male sterile, maintainer and restorer lines.
- Development of paprika varieties to meet high demand of non-pungent pods with high color value for oleoresin extraction industries.

Increasing industrialization, migration of populations to urban areas, a shortage of agricultural labor, shrinking cultivable land, increasing risks of crop failure due to unpredictable climate, emerging global markets and networks and increasing demand (domestic and export) for more nutritious and safer foods will affect future chilli breeding, production and marketing.

In general, chilli research in India should aim to deliver technologies pertaining to the following scenarios by integrating breeding research with multidiscipline:

- To address agricultural labor shortages, the development of cost-effective technologies pertaining to chilli seed production, chilli production, harvesting, processing and marketing will require close collaborative research between agricultural engineers and production scientists. Initial progress towards mechanization already has been made at several ICAR institutes, including IIHR (e.g. low-cost hand operated dibbler to facilitate sowing in protrays, tractor drawn bed former cum transplanter); these technologies should be evaluated and refined through participatory pilot projects in major chilli producing regions.
- To provide safe chilli products for domestic consumers and also to ensure smooth exports, agricultural policy must support research to control the presence of aflatoxin in dry chilli and related products.
- The share of improved chilli seeds (especially hybrids) within India will increase and there is also potential for seed export. It is imperative to provide support to the pepper seed industry while at the same time ensuring that hybrid seeds are available to small-scal**e** growers at affordable prices. The approaches undertaken by IIHR in the past decade on improved seed dissemination are realistic, as they not only support seed companies but also empower marginal farmers through community-based hybrid seed production. Similar approaches should be considered by other ICAR institutes and SAUs engaged in chilli breeding research to multiply the development impact from research.
- Organizing periodical consultation meetings of active stakeholders including private sector industries (seed, oleoresin, capsaicin extraction, and export) is critical to predict and identify future commercial domestic and international trade opportunities. Specific breeding research traits can then be identified and breeding plans can be executed by the interested stakeholders.

These advocacy actions would sustain and boost the Indian chilli industry by facilitating mutual benefit sharing among the stakeholders.

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