Pearl Millet

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Abstract

Pearl millet [*Pennisetum glaucum* (L). R. Br.] is cultivated on more than 8 million ha in India, ranking third after rice and wheat in acreage. It is an important source of staple food for human beings and valuable source of fodder for livestock in marginal environments. A significant portion of pearl millet grain is also used for non-food purposes such as poultry and cattle feed and alcohol extraction. Pearl millet improvement research in India is coordinated through the All India Coordinated Pearl Millet Improvement Project (AICPMIP) under the aegis of Indian Council of Agricultural Research (ICAR). Enormous accomplishments have been made in pearl millet improvement during the last 25 years. This chapter presents an overview of achievements in genetic improvement, cultural practices, disease and insect-pest management, seed production and value addition.

Germplasm from diverse genetic backgrounds and breeding materials with adequate disease resistance have been utilized in hybrid parental line breeding programmes leading towards development of hybrids with good adaptation to diverse production environments. During the last 25 years, a total of 115 improved cultivars were released, which provided a wider cultivar choice to farmers in various agro-ecological regions.

Agronomic research led to the establishment of detailed recommendations for agroecology specific pearl millet zones which made it possible to harness the yield potential of high-yielding hybrids and varieties.

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M. Singh, S. Kumar (eds.), *Broadening the Genetic Base of Grain Cereals*,
DOI 10.1007/978-81-322-3613-9_8

High-yielding hybrids and open-pollinated varieties (OPVs) have been widely adopted by Indian farmers. Currently, nearly 65 % of pearl millet area is under improved cultivars, mainly hybrids. A genetic linkage map of pearl millet has been developed, and quantitative trait loci (QTL) have been identified for traits of economic importance to facilitate molecular marker-assisted selection. Several processing technologies have been standardized to popularize pearl millet-based traditional and health food products. In the future climate change scenario, pearl millet being a highly climate resilient crop will play a greater role in providing food and nutritional security.

Keywords
Pearl millet • Evolution • Gene pool • Genetic diversity • Wide hybridization

8.1 Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is a highly cross-pollinated crop due to protogynous habit of flowering. Being a C_4 plant, it has a very high photosynthetic efficiency and dry matter production capacity. The crop adapts well to the driest and marginal soils than most other cereals. It is cultivated in the marginal environments where it encounters frequent drought, high temperatures, low and erratic rainfall and infertile soils with poor water-holding capacity. Pearl millet is grown as rainy season crop in north, while in south and northwest India, it may be grown in two or even three seasons a year. Pearl millet owing to its high drought tolerance potential occupies unique position in rainy season (*kharif*) crops. It also provides good quality fodder to cattle in the arid and semi-arid tropical regions and recognized as valuable forage crop because of its robust and fast growth habit. Its stalk is used for fuel and thatching.

In India, pearl millet is a primary source of dietary energy (360 k cal/kg) for rural population and the fourth most important cereal after rice, wheat and sorghum. It is a rich source of protein, calcium, phosphorous and iron. Pearl millet grain contains fairly high amounts of thiamine, riboflavin and niacin. Pearl millet grain is also used for non-food purpose such as poultry feed, cattle feed and alcohol extraction (Basavaraj et al. 2010). The exploitation of heterosis in pearl millet was considered easy with its protogynous flowering and high outcrossing rates (Rao et al. 1951; Chavan et al. 1955). However, the usual method of developing chance hybrids by taking advantage of the natural crossing was not successful in India in obtaining yield and uniformity of the desired level to make such hybrids a viable alternative to local landrace varieties. The availability and knowledge of cytoplasmic-nuclear male sterility (CMS), the development of CMS lines and their maintainers and restorers made it possible to produce the seed of commercial single-cross F_1 grain hybrids in India (Athwal 1966). Such hybrids had significant grain-yield advantage over popular open-pollinated varieties (OPVs). Mahadevappa and Ponnaiya (1966) recorded 4–157 % more grains yield in hybrids with CMS lines over CO I, the then OPV check. Moreover, these single-cross hybrids were phenotypically much more uniform than OPVs. At this stage, the prospect of hybrid breeding appeared bright (Rachie et al. 1967). In India, CMS has been exploited to realize grain-yield heterosis on farmers' fields. In fact, pearl millet grain hybrids using a CMS line from the USA were first developed in India in the mid-1960s (Athwal and Rachie 1963). Pearl millet hybrid using the same male-sterile line was also released for forage production in the southern coastal plain region of the USA in 1972 (Burton 1977).

Pearl millet grain hybrid intended for use in animal feed has been released in the same region. Significant heterosis has been demonstrated among variety/cross hybrids in experimental plots in Western Africa (Quendeba et al. 1993) where a large area of pearl millet is grown in a wide range of environments. At present about 70 % of pearl millet area in India is under improved cultivars, mainly hybrids. Following the adoption of high-yielding and disease-resistant cultivars, pearl millet productivity has gone up from 539 kg/ha during 1986–1990 to 1198 kg/ha during 2012–2013 registering a 73 % improvement, which is highest among all food crops.

8.2 Origin

Pearl millet originated in tropical Western Africa some 4000 years ago. From there, it differentiated into two races: *globosum* race that moved to the western side and the *typhoides* race that reached Eastern Africa and spread to India and southern Africa some 2000–3000 years ago. The evolution of pearl millet under the pressures of drought and high temperatures imparted the ability to tolerate drought, nutrient-deprived soil and extremes of temperature more effectively than other cereals like wheat and rice.

8.3 Distribution, Production and Productivity

Pearl millet accounts for about 50 % of the total area under all millets in the world. Pearl millet is cultivated on about 32 m ha in more than 30 countries of four continents, viz., Asia, Africa, North America and Australia. Pearl millet is cultivated on about 14 m ha in Africa and on about 12 m ha in Asia. Among all pearl millet growing countries, India has the largest area (>8 million ha) with 8.5 million tons of production. The developing countries in Asia and Africa contribute about 93 % of total millet production in the world. Asia alone contributes 43 % of world millet production. Recently pearl millet cultivation has expanded to 4–5 m ha area in Brazil. The states growing pearl millet in India are Rajasthan, Maharashtra, Gujarat, Uttar Pradesh, Haryana, Tamil Nadu, Andhra Pradesh and Karnataka, though the first four states account for >90 % of pearl millet acreage in the country.

Based on the wide range of environmental conditions under which pearl millet is grown in India and considering requirements for local adaptation, the whole pearl millet area has been divided into three zones, viz., A_1, A and B (Fig. 8.1). Zone A_1 is composed of parts of Rajasthan, Gujarat and Haryana receiving less than 400 mm annual rainfall. This zone accounts for about 4 m ha area, is highly drought prone and has light sandy soils with high temperatures. Zone A is composed of the remaining parts of the states of Rajasthan, Gujarat and Haryana and the entire pearl millet growing areas of other northern states like Uttar Pradesh, northern Madhya Pradesh, Punjab and Delhi. This zone has sandy loam soils and an annual rainfall of greater than 400 mm. Irrigation facilities are also available in some areas. Zone B is comprised of the southern states of Maharashtra, Karnataka, Tamil Nadu and Andhra Pradesh with rainfall greater than 400 mm, heavy soils and mild temperature conditions. The B zone has shorter days compared to A_1 and A zones. At present, about 75 % of the pearl millet is grown in A and A_1 zones, while B-zone accounts for the remaining area. This concept of zones was validated based on a 3-year hybrid trial study which indicated the existence of two distinct mega-environments corresponding to the AICPMIP's A- and B-zones (Gupta et al. 2013).

Most of pearl millet in India is grown during rainy (kharif) season (June–September) but is also cultivated during summer (February–May) in Gujarat, Rajasthan and Uttar Pradesh and during post-rainy (rabi) season (November–February) at a small scale in Maharashtra and Gujarat (Mula et al. 2009). During kharif season, pearl millet is largely grown as rainfed crop except in some areas in Eastern Rajasthan, Southern Haryana and Western Uttar Pradesh where supplemental irrigation is provided in case of shortage of rainfall during the crop season.

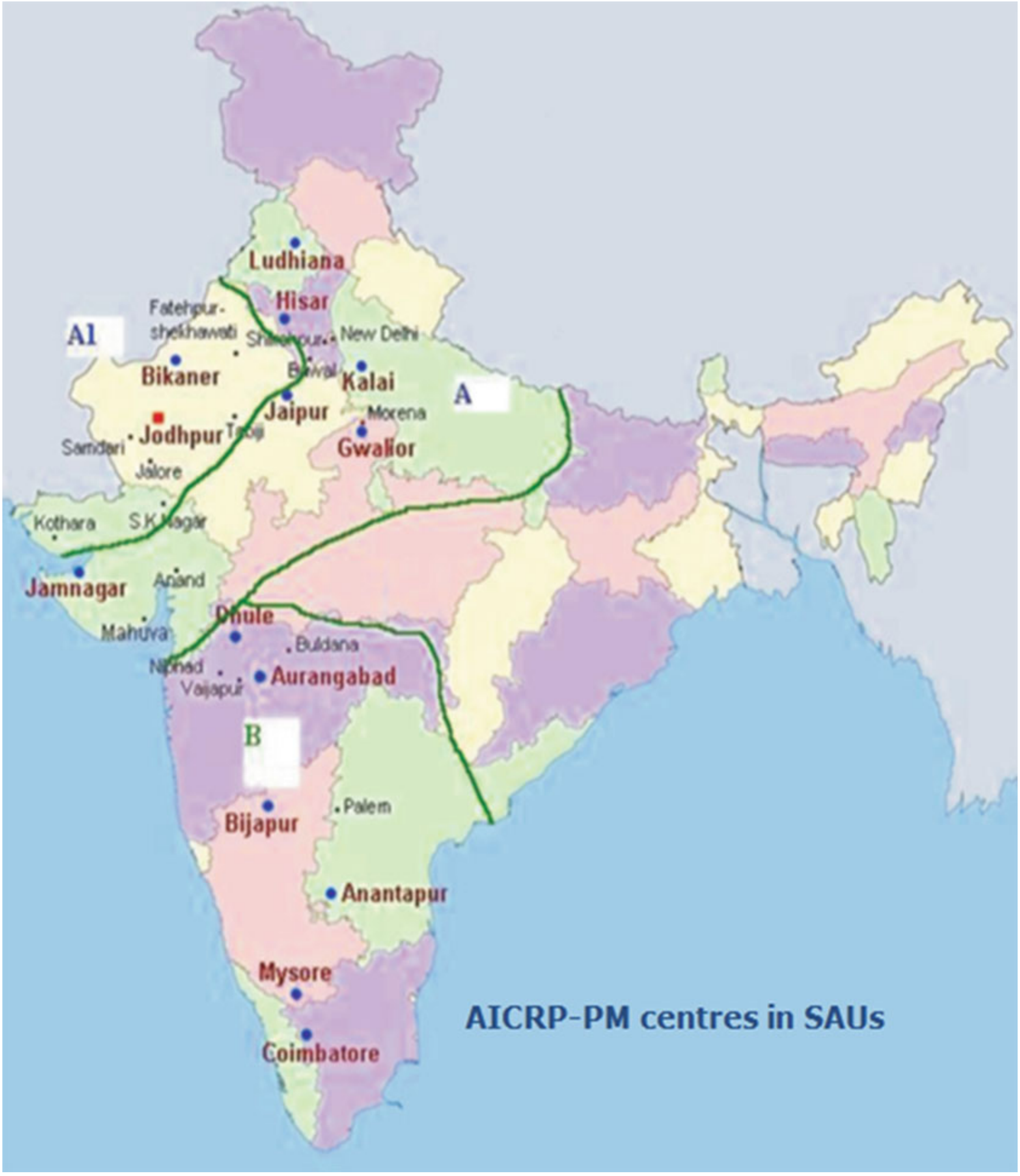

Fig. 8.1 Pearl millet growing zones of India

Summer season pearl millet is cultivated as an irrigated crop under high levels of agronomic management. Yields of more than 50 q/ha have been experienced in FLDs and 70 and 80 q/ha were achieved in national demonstrations with good management practices.

8.4 Research Prioritization

Pearl millet is cultivated under diverse agroecologies in different regions. The growing conditions vary from better-endowed environments with high-external input to highly drought-prone environments. This necessitates prioritization of research in relation to production constraints and differential requirement of various crop-growing regions.

8.4.1 Abiotic Constraints

Pearl millet is mostly (>92 %) cultivated under rainfed conditions in the arid and semi-arid regions of country where annual rainfall ranges from 150 to 750 mm, most of which is received during June to September (Harinarayana et al. 1999). Owing to its cultivation in rainfed systems, its cultivation is challenged by several abiotic stresses. Among abiotic constraints, drought affects this crop the most and is caused due to low and erratic distribution of rainfall. The coefficient of variation of annual rainfall ranges from 20 to 30 % leading to variable drought conditions within and between crop seasons. Hence, the development of pearl millet cultivars suitable for rainfed and unpredictable low-rainfall situations has been a priority area in crop management. Average rainy season maximum and minimum air temperatures (°C) in India are around 35 °C and 25 °C, respectively. The maximum air temperature around 43 °C is common in the beginning of rainy season crop. The soil surface temperatures during germination may reach 60–62 °C in the Indian arid zone. Formation of crust is also common in soil with high-silt contents. Both of these factors lead to the disturbed plant stand. Hence, cultural interventions have been explored to get improved emergence and adequate plant stand crop geometry, weed control and water management to optimize crop yields in drought-prone environments have also been worked out. Soils in the regions where pearl millet is cultivated are often infertile as they contain low amount of organic matter (0.05–0.40 %) because of low vegetation cover, coarse texture of soils and prevailing high temperatures (Kumar et al. 2009). Soils also contain low to medium levels of available phosphorous (10–25 kg/ha). Organic fertilizers are rarely applied resulting in extremely nutrient-depleted soils. Therefore, research on nutrient management has been a critical component of research in order to increase and stabilize the crop productivity. Pearl millet is also grown with supplemental irrigation with high input and management condition in small pockets scattered throughout the pearl millet growing regions. The environmental resources in such blocks are sufficient enough to support high levels of productivity to obtain a maximum return for the input supplied. Hence, maximization of yield under high crop management is also an important research priority.

Pearl millet cultivation has recently occupied large areas in irrigated summer season (February–June) crop in parts of Gujarat, Rajasthan and Uttar Pradesh where high temperatures (>42 °C) are of common occurrence during flowering. This crop faces high air temperatures during flowering leading to high reproductive sterility which finally leads to drastic yield reduction. However, a few hybrids from some of the seed companies (e.g. 86 M 11 and Proagro 9444), which specifically target this environment for hybrid development, have been found having good seed set and high grain yield of the order of 4–5 t/ha. Based on multilocation and multi-year screening in target ecology, large genetic variation for tolerance to heat at reproductive stage among pearl millet breeding lines and populations has been observed, and heat-tolerant lines have been identified. These include several maintainer lines (ICMB 92777, ICMB 05666, ICMB 00333, ICMB 01888, ICMB 02333 and ICMB 03555), improved populations (ICMV 82132, MC 94, ICTP 8202 and MC-Bulk) and germplasm accessions (IP 19799, IP 19877 and IP 19743) (Gupta et al. 2015a, b).

8.4.2 Biotic Constraints

Pearl millet production is confronted with relatively few biotic stresses as compared to other crops. Among the diseases, downy mildew (*Sclerospora graminicola*) is the most important constraint, especially on genetically uniform hybrids. Other diseases include smut (*Moesziomyces penicillariae*), rust (*Puccinia substriata* var. *indica*), blast (*Pyricularia grisea*) and ergot (*Claviceps fusiformis*). Development, screening and evaluation of germplasm, breeding material and hybrid parental lines for their reaction to various diseases are hence integral components of research. Although many insects have been reported in pearl millet, only a few of them are of some, albeit little, economic importance in causing losses to the crop. The insect-pest incidence on commercial cultivars and experimental test genotypes needs to be closely monitored during crop seasons.

8.4.3 Addressing Utilization Constraints

Enhancing the utilization of pearl millet as food is constrained by the property of its flour to acquire a rancid smell within 7–10 days of milling because of high concentration of lipids that contribute to the development of fat acidity, lipolytic activity and accumulation of peroxide of lipids in the meal during storage. Another constraint is the presence of various anti-nutrients like phytate and polyphenols which affect the nutritional quality and interfere with mineral bioavailability, inhibit proteolytic and amylolytic enzymes and reduce the protein and starch digestibility. Polyphenols also affect the nutritional quality and interfere with mineral bioavailability and protein digestibility by inhibiting the activity of several enzymes. Several processing techniques have been explored to circumvent these constraints and develop value-added food products with enhanced shelf life.

8.5 Genetic Improvement

8.5.1 Germplasm Utilization

Utilization of diverse germplasm is very critical to broaden the genetic base of cultivars. Hybrid parents in pearl millet, both seed parents (A-lines) and restorer parents (R-lines), have been bred utilizing germplasm for different geographical regions. A-lines have been bred utilizing significant germplasm of African origin, while locally adapted Indian material was used in breeding R-lines in most of public and private sector hybrid programmes. For instance, trends in utilization of genetic resources at ICRISAT suggest that a wide range of germplasm, composites, elite lines and crosses between these three groups have been used in the breeding of both maintainer (B-) and R-lines of hybrids (Table 8.1). The nature of germplasm, composites and elite lines that have gone into the development of B- and R-lines varied enormously. This was clearly reflected in the molecular characterization data of diversity among B- and R-lines developed at ICRISAT. In a recently conducted study at ICRISAT, genetic diversity pattern between two groups of parents was investigated, bred till 2004 (Set I) and developed during 2004–2010 (Set II). Combined analysis of 379 hybrid parents (current 166 parents and 213 previously developed hybrid parents) carried out using a set of highly polymorphic 28 SSRs detected 12.7 alleles per locus. Distance matrix differentiated these currents and previously developed hybrid parents into two separate clusters, indicating infusion of new genetic variability over time as reflected by the involvement of more

Table 8.1 Type of material used in the development of designated maintainer (*B*) and restorer (*R*) lines of pearl millet bred at ICRISAT during 1981–2004

Type of genetic material	No. of lines derived		Remarks
	B-lines	R-lines	
Germplasm	3	19	Inbreeding and selection directly from germplasm
Composites	9	11	Includes composites and open-pollinated varieties
Germplasm × elite line	21	8	Includes early-generation breeding lines derived from crosses between germplasm and elite lines
Composite × elite line	19	17	Includes early-generation breeding lines derived from crosses of composites and elite lines
Elite line × elite line	47	59	Includes crosses between elite lines from advanced generations

genotype-specific alleles. Also, the seed and restorer parents were found clearly separated from each other in both sets with few crossovers, indicating the existence of two diverse and broad-based pools in hybrid parents of pearl millet. Results suggested that newly developed lines were as much divergent when compared with previously developed lines, indicating that current ICRISAT pearl millet breeding programme was moving towards the development of diverse new hybrid parental lines Fig. 8.2.

Germplasm from different regions has also been used to develop a large number of composites (Rai and Anand Kumar 1994) which have been further utilized in the development of different open-pollinated varieties (OPVs) following recurrent selection. Many pearl millet varieties such as WCC75, ICMV 155, ICTP 8203, CZP 9802, Raj 171, ICMV 221, JBV 2 and JBV 3 were developed from germplasm.

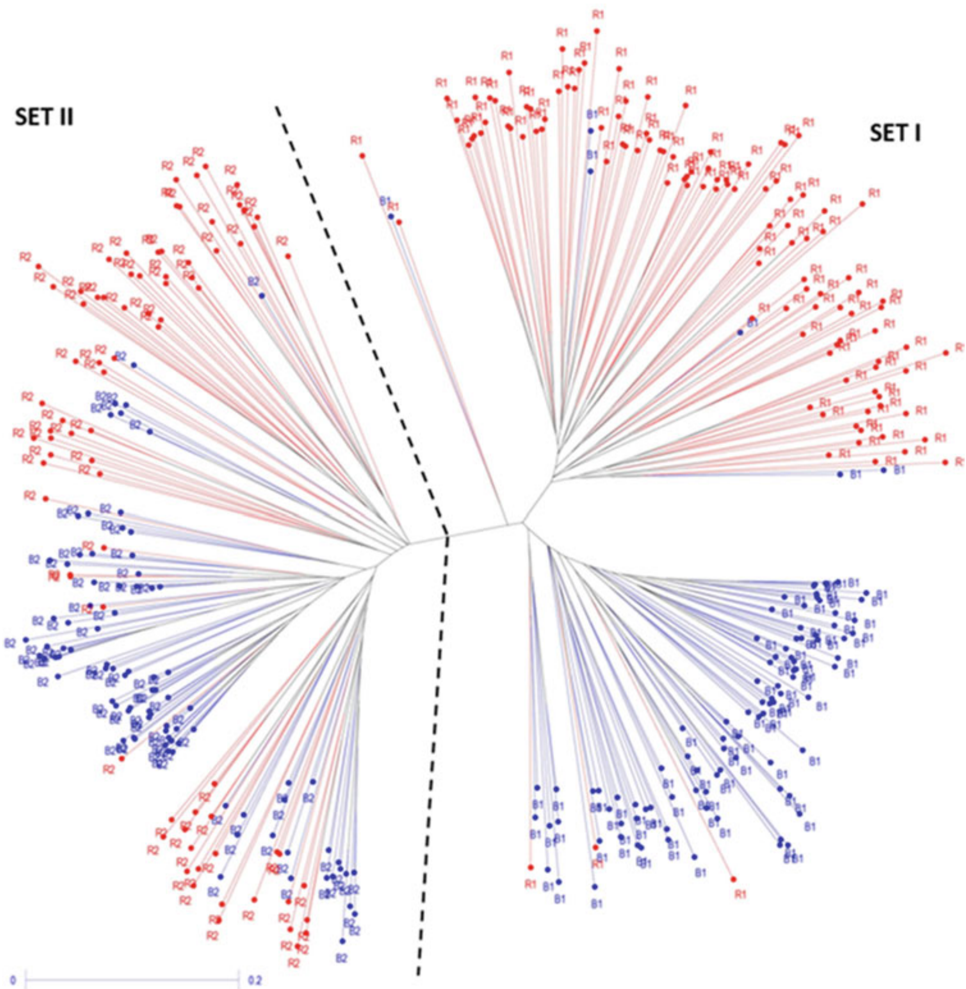

Fig. 8.2 Unweighted neighbour-joining tree based on a simple matching dissimilarity matrix for allele sizes detected by 28 simple sequence repeat primer pairs across 379 pearl millet hybrid parental lines (213 set I lines and 166 set II lines). Accessions are identified as "B" for seed parental lines and "R" as restorer lines. Suffix 1 and 2 with B- and R-lines represent set I and set II lines, respectively. B-lines are shown in *blue* and R-lines in *red colour* (Gupta et al. 2015b)

8.5.1.1 Development of Seed Parents

Considering the availability of a diverse range of restorers available in the Indian pearl millet breeding programmes and a serious lack in the number and diversity in seed parents, NARS and ICRISAT prioritized its research with much greater emphasis on seed parents' development.

8.5.1.2 Improving Male-Sterile Lines

In the breeding of seed parents (A-lines), high grain-yield potential of A-lines, both as lines per se and in hybrids (i.e. combining ability), is the most important consideration. Thus, high yield potential is the first target trait for which selection is made visually in un-replicated nurseries. High yield, coupled with other agronomic and farmer preferred traits, is targeted in A-line breeding. Some of the traits considered for all the environments include lodging resistance, compact panicles, good exertion and seed set, while regional preferred traits, like maturity, plant height (grain vs. dual purpose), tillering ability, seed colour and seed size, are specific to different agroecologies. Most of these agronomic traits have high heritability for which visual selection during advance generations is fairly effective. The A lines must also have complete and stable male sterility, and B-lines must have profuse pollen production ability across the seasons and sites. The d_2 dwarf plant height has emerged as the most dominant plant type concept in seed parent breeding. This has several operational advantages: (i) it provides the option for breeding hybrids of varying heights, (ii) it provides greater control on seed yield and quality by reducing the risk of lodging that can occur under high management seed production conditions, and (iii) it allows a much rapid detection and efficient rouging of off-types and pollen shedders in A lines. A large number of designated A lines bred represent considerable morphological diversity for the agronomic traits. In view of the increasingly important role of the stover, seed parent development programme is targeting medium and late maturity duration. New plant types such as A lines with long panicles (30–80 cm compared to standard normal of 10–20 cm), thick panicles (40–50 mm diameter compared normal 20–30 mm) and large seed size (17–20 g of 1000-seed mass compared to standard normal of 9–12 g) are being developed at ICRISAT and many All India Coordinated Pearl Millet Improvement Centres. Progenies are evaluated for downy mildew resistance during the generation advancement of breeding lines which runs concurrent to agronomic evaluation to ensure that B- and R-lines finally produced are resistant to this disease.

8.5.1.3 Genetic and Cytoplasmic Diversity

The male-sterile lines and pollinators being used to develop superior hybrids should be diverse in genetic and cytoplasmic nature.

8.5.1.4 Genetic Diversification of Male-Sterile Lines

Till date A_1 CMS has been the most stable source of male sterility in pearl millet hybrid breeding. This source continues to be the only one involved in almost all the commercial hybrids produced so far. It also continues by far to be the most extensively used source in seed parent breeding. As a consequence a large number of male-sterile lines developed with this source are now available, especially in India ICRISAT alone developed and disseminated more than 90 male-sterile lines of diverse genetic backgrounds and with diverse morphological characteristics during 1971–2013.

8.5.1.5 Cytoplasmic Diversification

Burton and Athwal (1967) studied the relationships between cytoplasms of Tift 23A, L66A and L67A. They crossed all the three CMS lines with each of their respective maintainers (B-lines) and also to some of the restorers (R-lines). Based on the fertility/sterility reaction as measured by seed set in A × B hybrids, genetic models were proposed for A-, B- and R-lines. Several other CMS sources were identified in the following years. For instance, Appadurai et al. (1982) developed a CMS line PT732A and showed its cytoplasm to be different from that of Tift 23A. Aken'Ova and Chheda (1981) identified male-sterile plants in a Nigerian pearl millet population (ex-Bornu), a gero millet. In later studies, Aken'Ova (1985) crossed Tift 23B$_1$, Tift 238B$_2$ and L67B (sterility maintainers of A$_1$, A$_2$ and A$_3$, respectively) with ex-Bornu male-sterile line. All the three maintained sterility in crosses with ex-Bornu source but not as well as did gero-B (the selfed progeny of an ex-Bornu line) which was an excellent maintainer for ex-Bornu source of CMS. Gero-B maintained sterility in Tift 23A and L67A sources but was a partial fertility restorer of the Tift 239A$_2$. Tift 186 which was reported to be a maintainer for A$_1$, A$_2$ and A$_3$ sources restored fertility in ex-Bornu, confirming that male sterility identified in ex-Bornu was a new CMS source. Based on the similar field studies of male fertility restoration in hybrids, Marchais and Pernes (1985) identified a cytoplasm from an accession of *P. glaucum* subsp. *violaceum* from Senegal and showed its male sterility to be different from the A$_1$, A$_2$ and A$_3$ cytoplasms. However, in studies involving near-isonuclear lines, it was found that this cytoplasm had considerable resemblance with A$_1$ system (Talukdar et al. 1987). This CMS source was designated as Av. Hanna (1989) identified a cytoplasm from another accession of *P. glaucum* subsp. *monodii* (*violaceum*) from Senegal and showed its male sterility to be different from the A$_1$, A$_2$ and A$_3$ cytoplasms. This new cytoplasm has been designated as A$_4$. Rai and Hash (1990) observed significant effect of nuclear genetic background on the fertility restoration patterns of hybrids and suggested that isonuclear lines (the same nuclear genome transferred into different cytoplasmic backgrounds) should be used for reliable classification of CMS sources in pearl millet. Using isonuclear A-lines, Rai et al. (1996) showed that male sterility from the above two wild species sources are different from each other as well as from the A$_1$, A$_2$ and A$_3$ sources. Several other CMS sources identified at ICRISAT, in the Indian national programmes and elsewhere were shown either to be no different from the A$_1$ CMS system or had no more stable male sterility and hence were of little applied value. Among the other CMS sources, the PT732A source has been mostly used at the Tamil Nadu Agricultural University, and the A$_2$ and A$_3$ sources have been largely used in seed parent breeding at the Punjab Agricultural University. Both of these have had problems with high levels of pollen shedders in their A lines. Good maintainers of these three CMS sources are very infrequent in the breeding materials, limiting their utility in genetic diversification of A lines. Other CMS sources have either not proved better than the A$_1$ or have not been properly characterized. Research shows that among all the reported CMS sources, the A$_4$ and A$_5$ have more stable male sterility than the A$_1$ source (Rai et al. 2009). Restorers of the A$_4$ and A$_{egp}$ occur in materials of diverse origin, indicating their greater immediate utility in breeding seed parents of grain hybrids. For breeding seed parents of forage hybrids, the A$_5$ CMS source may be the best one as virtually any inbred is a potential maintainer of it and hence can be converted into an A-line. Restorer sources of A$_5$ are hard to find (Rai 1995). However, its restorer genes have now been discovered, paving the way for the potential utility of this CMS source in breeding seed parents of grain hybrids as well. The use of the A$_4$ source in seed parent breeding has already begun in several hybrid breeding programmes in India and the USA. CMS lines were bred on A$_1$, A$_2$, A$_3$ and other sources and exploited for commercial production of hybrids.

8.5.1.6 Stability of CMS Systems

It was observed that all the male-sterile lines based on A$_1$ CMS system produce varying, albeit low, frequencies of pollen shedders, which is influenced by the genetic background of A-lines and the environments in which they are grown. At the same time, it had also been established that A$_2$ and A$_3$ CMS systems were unstable for male sterility (Rai et al. 1996). In order to assess the stability of alternative CMS sources, viz., A$_{egp}$, A$_4$ and A$_5$ vis-à-vis that of A$_1$, isonuclear A-lines with four cytoplasms (A$_1$, A$_{egp}$, A$_4$ and A$_5$) in each of the three diverse nuclear genetic backgrounds (81B, 5054B and ICMB 88004) were evaluated for pollen shedders in six environments created by three planting dates (rainy season, early summer and late summer season) for 2 years. The results showed that the frequency of pollen shedders was higher in A-line with the A$_1$ cytoplasm (0.0–2.5 %) as compared to the A$_4$

Table 8.2 Percent pollen shedders in isonuclear A-lines of pearl millet in the background of four cytoplasms

Genotype	Pollen shedders (%) in cytoplasm			
	A_1	A_{egp}	A_4	A_5
81B	0.3–0.6	0.0–0.1	0.0	0.0
5054B	0.1–2.5	0.0	0.0–0.3	0.0
ICMB 88004	0.0–0.6	0.0–0.1	0.0–0.1	0.0

cytoplasm (0.0–0.3 %) and the A_{egp} cytoplasm (0.0–0.1 %) (Table 8.2). There were no pollen shedders in A-lines with the A_5 cytoplasm, irrespective of their genetic backgrounds or the environments in which they were grown.

8.5.1.7 Prioritization of CMS Systems

Considering the key attributes of the CMS systems as mentioned above, the highest priority should be on breeding A-lines with the A_5 and A_4 CMS systems. A beginning has been made in this direction at ICRISAT and AICPMIP centres, as reflected in the increasing proportion of A-lines with the A_4 cytoplasm, followed by the A_5 cytoplasm (Table 8.3). Additional advantage is that the genetic background of male-sterile lines in A_4 and A_5 cytoplasms does not affect the fertility restoration of hybrids, whereas the genetic background of A_1 cytoplasm has significant effect on the fertility restoration (Gupta et al. 2010). Hence, ICRISAT focused on greater use of the A_4 and A_5 CMS systems for breeding a diverse range of A-lines. Thus, during the last 18 years (1996–2013), ICRISAT developed and disseminated 150 A-lines to the public and private sector breeding programmes, of which 64 are based on A_1 CMS system, 68 on A_4 CMS system and 16 on A_5 CMS system. A recent consultation meeting with hybrid parent users also suggested increase in cytoplasmic diversification and hence recommended greater use of the A_4 and A_5 CMS systems in A-line breeding (Rai et al. 2012). However, it would require a major shift in breeding efforts for restorer development as a high proportion of the restorers of currently most exploited A_1 CMS system in all the hybrid programmes in India and elsewhere fail to restore the fertility of hybrids made on A-lines based on the A_4 and A_5 CMS systems.

8.5.2 Restorer Parents

While higher frequency of maintainers is a positive attribute for A-line development, the implied low frequency of restorers makes it a negative attribute for restorer line (R-line) development. Thus, to make the A-lines of new CMS systems commercially attractive, greater efforts would be required to breed their restorers. Considering the medium to high frequency of restorers in a diverse range of populations mentioned earlier, inbreeding and selection can be usefully practiced to develop restorer lines of the A_1 and the A_4 CMS systems.

8.5.2.1 Restorer Lines

Restorer lines must produce profuse pollen that should remain viable at air temperatures as high as 42–44 °C. Also pollen parents must produce highly fertile hybrids, which confer some degree of protection from ergot and smut infection. Besides being able to produce high-yielding hybrids, the restorers should also be highly productive which is important from the viewpoint of seed production economy. It is desirable to breed pollinators of 150–180 cm height, but no shorter than the A-line with built-in attributes of panicle, maturity and tillering that will be preferred by farmers in the hybrids. Pollinators must have acceptable level of lodging resistance and should also possess adequate levels of resistance to various diseases.

8.5.2.2 Diversification of Restorers

So far, almost entire emphasis in restorer breeding has been on the utilization of the A_1 CMS system. Hence, excellent restorers of this CMS system are abundantly available. But there is a serious lack of the A_4 and A_5 restorers in elite agronomic genotypes. However, excellent genetic stocks of A_4 and A_5 restorers developed at ICRISAT are being used in backcross breeding for the development of restorer lines of A_4 and A_5 CMS systems. An efficient backcross breeding method for converting elite inbred lines into their A_4 and A_5 restorer versions has been developed. Also, moderate and low frequency of restorers of the A_4 and A_5 CMS systems, respectively, have

Table 8.3 Number of male-sterile (*A*-) lines developed in background of different CMS systems at AICPMIP centres and ICRISAT

Period	Number of designated A-lines				
	A_1 cytoplasm	A_4 cytoplasm	A_5 cytoplasm	Others	Total
AICPMIP centres					
1986–2011	157	30	3	25	215
ICRISAT					
1986–1995	26	1	0	0	27
1996–2004	32	31	4	1	68
2005–2013	32	37	12	0	81
Total	243	90	14	26	373

been found in most of the populations surveyed. Their frequency in these populations can be rapidly increased by recurrent selection as shown for the A_1-system restorers.

8.6 Cultivar Development

Earlier efforts in pearl millet improvement in India concentrated on the utilization of local germplasm material. Using simple mass selection, a few varieties were developed. The introduction of material in the 1960s from African countries yielded useful varieties for Indian conditions. Jamnagar Giant, Improved Ghana and Pusa Moti were developed by selection from African introductions. Since pearl millet is a highly cross-pollinated crop and displays a high degree of heterosis for grain and stover yields, attempts were made in the 1950s to exploit heterosis in hybrids by utilizing the protogynous nature of flowering to produce chance hybrids and to raise crop productivity. The chance hybrids, however, could not become popular due to their limited superiority over OPVs, narrow range of adaptation and lack of seed production programmes.

8.6.1 Single-Cross Hybrids

CMS is used for developing high-yielding single-cross hybrids (SCH) of pearl millet. This is achieved by identifying a specific combination of a male-sterile line (seed parent) and an inbred (male parent pollinator) resulting in a high-yielding fertile hybrid, the seed of which can be multiplied economically. Exploitation of heterosis became a reality with the discovery of cytoplasmic-nuclear male sterility and release of male-sterile lines Tift 23A and Tift 18A in the early 1960s at Tifton Georgia, USA. These lines were made available to Indian breeding programmes. The male-sterile line Tift 23A was extensively utilized because of its semi-dwarf stature, profuse tillering, uniform flowering and good combining ability. As a result, a few hybrids based on this line were released between 1965 and 1969. One of these hybrids (HB 3) became highly popular and was extensively cultivated because of its early maturity, bold grains and adaptation to drought.

The development of single-cross hybrids started with the availability of male-sterile line Tift 23A (Athwal 1966). The spectacular yield advances that were achieved (Athwal and Rachie 1963) stimulated several breeders to make and test new hybrid combinations. During the last 42 years (1965–2012), a large number of pearl millet hybrids were identified and released in India for general cultivation (Khairwal et al. 2007). Although the numbers of hybrids bred are many, only a few became popular among farmers. Some public sector hybrids HB 3 (Tift 23A × J I04), BJ 104 (5141A × J 104), BK 560 (5141A × K 560–230), MH 179 or ICMH 451 (81A × ICMP 451), Pusa 23 (841A × D 23), HHB 50 (81A × H 90-4-5) and HHB 67 (843A × H 77/833-2) and at least five private sector hybrids (including MBH 110, GK 1004, PB9444 and MLBH 104 and 86 M86) have been widely grown, whereas CJ 104 (5054A × J 104), PHB 14 (IlIA × PIB 228) and HHB 60

(8lA × H77/833-2) have been restricted to specific areas. If we trace the pedigree of popular released pearl millet hybrids, we would recognize only a limited fraction of the available genetic resources that have been exploited so far. Almost all pearl millet hybrids in India are still based on Tift 23B. Similarly, a handful of pollinators, especially J 104, K 560 and H77/833-2, have been repeatedly used in the national programmes in India. CCS HAU, Hisar, released nine pearl millet hybrids by utilizing only few pollinators (H90/4-5, H77/833-2, G73-l07, H77/29-2 and HBL-lI) and four male-sterile lines that were related to Tift 23A (Khairwal et al. 2007). Intensive cultivation of hybrids based on a single male-sterile line, however, led to downy mildew epidemic in the mid-1970s (Govila et al. 1997).

Using diverse male-sterile lines and pollinators, a large number of hybrids have been released in India during the last 25 years by both public and private sectors. A total of 107 improved cultivars were released since 1986. Three-fourth of these was hybrids which showed that hybrid breeding has been a major priority in India in pearl millet. The number of releases over a period of 25 years indicates that, on an average, 3–4 hybrids are released each year for general cultivation for different agro-ecological zones. Additionally, private sector seed companies have marketed significant number of hybrids as truthfully labelled seed. This has enabled farmers to choose from a wide range of available cultivars with appropriate trait combinations that they consider fit to meet their requirement in different crop production environments of various states. This cultivation of a large number of hybrids also helped in providing buffering mechanism against diseases, insect pests and environmental vagaries. Since 1986, 53 hybrids from public sector and 35 from private sector have been notified for different regions. These hybrids include HHB 45, HHB 50, MH 179, Pusa 23, GHB 30, HHB 60, HHB 67, MLBH 104, MBH 110, Eknath 301, ICMH 356, Shradha, Saburi, JKBH 26, 7686, 7688, HHB 68, HHB 94, HHB 146, HHB 117, HHB 67 Improved, RHB 121, GHB 538, GHB 558, GK 1004, Proagro 9444, GHB32, ICMH45l, MBHllO, Pusa23, Pusa332, PHBl08, ICMH356, PB9444, 86 M86 Nandi 5, JK26, RHB121 and HHB197, HHB 223, RHB 177, MHB 17 and 86 M64.

Experiencing recurrent problems of downy mildew in hybrids in the 1970s and 1980s, AICPMIP and ICRISAT responded by increasing the efforts to breed open-pollinated varieties (OPVs) and by strengthening the research to diversify the genetic base of seed parents. As a result, many OPVs like ICTP 8203, WCC 75, HC 4, HC 10, HC 20, ICMV 155, ICMV 221, CZP 9802 and Raj 171 were adopted by growers at a large scale. Contrary to hybrids, there is no risk of breakdown of resistance of OPVs to downy mildew. The OPVs are currently being released for risk-prone areas where replanting is a common practice.

8.7 Molecular Breeding

8.7.1 Genetic Linkage Map

Efforts towards molecular breeding started in pearl millet in the early 1990s with the development of a molecular marker-based genetic linkage map which largely comprised of RFLP loci (Liu et al. 1994). This linkage map was short (circa 300 cM), but it has now been expanded (Qi et al. 2004), and current genetic linkage map of pearl millet covers 1148 cM (Supriya et al. 2011), and SNP markers have also been included (Bertin et al. 2005; Sehgal et al. 2012). The most recently published, well-saturated genetic linkage map of pearl millet provides coverage with 321 marker loci (258 DArTs and 63 SSRs) distributed over 1148 CM (Supriya et al. 2011).

8.7.2 Quantitative Trait Loci Mapping and Marker-Assisted Selection

Initial map was followed by identification of QTLs using several different mapping populations. The target traits for pearl millet QTL mapping have been downy mildew resistance, grain and stover yield under favourable conditions, stover quality and iron and zinc concentrations in pearl millet grain.

8.7.3 Downy Mildew Resistance

Several putative QTLs have been identified that determine a significant proportion of downy mildew resistance in pearl millet (Hash et al. 1997). Downy mildew-resistant version of an early-maturing hybrid HHB 67 has been released as HHB 67 Improved for drought-prone areas in the states of Rajasthan, Haryana and Gujarat. It is suggested that resistance pyramiding conferred border or broader spectrum than expected based on the performance of parents involved. It is further recommended that host plant resistance deployed in genetically uniform hybrids be backstopped with appropriate management practices (crop and cultivar rotation and the use of appropriate prophylactic fungicidal seed dressings) to extend the useful economic life of this resistance (Hash et al. 1997, 1999; Witcombe and Hash 2000; Hash and Witcombe 2002).

8.7.4 Drought Tolerance

Because of intrinsic difficulties in breeding for drought adaptation by conventional breeding (Barker et al. 2005; Blum 1988), this field has become a prime focus for molecular marker-assisted breeding. Genetic mapping for drought tolerance has targeted terminal drought. Several major QTLs have been identified that have significant effects on pearl millet yield in drought-stress environments (Bidinger et al. 2005; Yadav et al. 2002, 2004). In addition, a number of other QTLs were detected that were associated with maintenance of grain-yield-determining component traits (Yadav et al. 2011). There are reports that the LG 2 QTL is also (not mentioned earlier) associated with salinity tolerance (Sharma et al. 2011), presumably as a result of its effects on transpiration rate.

8.7.5 Stover Quality

Efforts are under way to use marker-assisted breeding for enhancement of stover quality (Hash et al. 2003). Two QTLs one each on LG 2 and LG 6 have been identified which govern several fodder quality traits. It seems that the improved stover quality conferred is likely due to improved host plant resistance to blast (Nepolean et al. 2010).

8.8 Seed Production and Supply

In the last 25 years, great progress has been made in terms of seed production and processing by using high-yielding seed parents, adoption of improved production technologies by seed producers and modernization in seed processing and packaging technologies. Both public and private sectors are involved in pearl millet seed production and distribution. The major share in marketing of improved pearl millet seed comes from private sector because of involvement of hybrid cultivars. However, public sector also plays very vital role in providing seed of improved cultivars at reasonable price to the farmers.

8.8.1 Planning

Planning is a very important aspect of seed production. Need assessment is the first most important step in production planning to produce adequate quantity of all states and allocates seed production programme to various seed-producing organizations. Depending upon the sale projections of a particular hybrid and inventory stock of various classes of seed with acceptable quality, private companies also work out requirements for foundation and breeder seed. An example of the method for calculating quantity of different classes of seed and land requirement for pearl millet seed production is given in Table 8.4. Thus, it can be seen that total annually required quantity of breeder seed of A-, B- and R-lines is

Table 8.4 Area and seed requirement for various seed classes to produce 22,000 tons (enough to plant 5.5 million ha) of certified pearl millet hybrid seed

	Year 1 Season I		Year 1 Season II		Year 2 Season I	
	For *breeder seed* (BS) production		For *foundation seed* (FS) production		For *certified seed* (CS) production	
Parental line	Area (ha)	Nucleus seed quantity (kg)	Area (ha)	BS quantity (kg)	Area (ha)	FS quantity (kg)
A-line	0.352	1.408	88.0	352.0	22,000	88,000
B-line	0.088	0.352	22.0	88.0	–	–
R-line	0.088	0.352	22.0	88.0	5500	22,000
Total	0.528	2.112	132.0	528.0	27,500	110,000

The calculations assume 1000 kg/ha of seed yield in production plots, 4 kg/ha of seed rate and female/male row ratios of 4:1

528 kg to ultimately produce 22,000 tons of hybrid seed that is sufficient enough to plant an area of 5.5 m ha. The total area to produce required breeder seed is 0.53 ha only which is equal to a plot size of 73 m × 73 m. Such small seed quantity needed to produce breeder seed to meet the huge certified seed demand shows the massive seed production potential of pearl millet. Thus, only 110 tons of foundation seed of hybrid parental lines are required to fulfil the current requirement of certified hybrid seed, and 27500 ha area is needed to produce certified seed of hybrids. The whole seed production chain is completed in three seasons (1½ year).

The most critical component in foundation and certified hybrid seeds is to ensure adequate isolation distance for which planning is very critical. This requirement can be easily fulfilled through seed village concept to undertake seed production programme in nontraditional area in Telangana during summer season. Carry-over strategy is a very critical component of planning. Carry-over seed is produced as a buffer stock to insure against sudden demand or unforeseen shortfalls due to vagaries of nature. A general limit of carry-over seed in pearl millet is 100 % for breeder seed, 50 % for foundation seed and 20 % for certified seed.

8.8.2 Production Chain

Seed production and supply chain in India are very well developed for pearl millet and involve multiplication process of various classes (nucleus, breeder, foundation and certified). Commercial seed production chain starts from breeder seed, which is produced by AICPMIP centres, SAUs, ICRISAT and some private companies. Foundation seed of OPVs and parental lines of hybrids is produced by the National Seed Corporation (NSC), State Farms Corporation of India, State Seed Corporation (SSCs) and some seed companies. Certified seed of released and notified cultivars is mainly produced by SSCs and NSC following established procedure of seed production which starts from compiling of indents by the Government of India that is passed on to the Assistant Director General (Seeds), Indian Council of Agricultural Research, who in turn, passes on the indents to the Project Coordinator (Pearl millet). The Project Coordinator allots the breeder seed production of OPVs and hybrid parental lines to different originating centres and monitors the production programme. The breeder seed produced is then passed on to the indenting agencies to enable them to use it in foundation seed production. Private sector is involved in large-scale seed production of public bred hybrids as well as their own proprietary hybrids. The multiplication and distribution of certified seed of public hybrids like Pusa 23, HHB 67, HHB 67 Improved, HHB 197 and OPV (ICTP 8203) by the private sector is one example contributing towards the common goal of farmers' benefit. Private sector also produces large quantities of truthfully labelled seed which need not be certified by the seed certification agencies. The quantity of such seed produced and marketed by the private sector is yet to be assessed.

8.8.3 Production Calendar

The certified seed production programme is organized primarily in farmers' fields by various seed corporations and private companies and is undertaken in South India. Almost 80 % of total seed is produced during summer (January–April) in Telangana. After harvesting and processing, the seed is then dispatched to the target area. This cycle of seed production reduces the overhead cost as no seed storage is required for long. Some seed is produced during the rainy season in Andhra Pradesh and Karnataka to meet any deficit. However, rainy season seed production sometimes is risky due to pollen wash and ends up with lower seed yields. Seed quality is also not as good as that obtained from summer production.

8.8.4 Production Technology

Substantial refinement in seed production technology has taken place in the recent past. Planting time, planting ratio of male and female parental lines of hybrids and agronomic and fertilizer management have been worked out to maximize the yields in production plots. In certified seed production plot of hybrids, 8:2 ratio of A- and R-lines is followed to economize the seed production. Seed yield, often in the range of 1000–1200 kg/ha, is easily obtained as seed production is undertaken under high agronomic management. However, the yield of parental lines is determined by their genetic potential. Yield levels in seed production plots are also influenced by climate, soil conditions and crop management.

8.8.5 Seed Quantity

There has been no shortfall in the supply of indented breeder seed in any of the variety or hybrid parental lines. Each year, on an average, 20,000 metric tons of hybrid seed is produced that is sufficient to cover more than 60 % of total pearl millet area, which is highest among crops in India in which hybrids are preferred as choice of cultivar types. There is still a great scope to future further improve the quality and seed availability of improved cultivars.

8.9 Alternative Uses and Value Addition

Unfermented bread (*chapatti*) is the most common food made from pearl millet in rural households, followed by other traditional products like thin porridge (*khichdi*) and thick porridge (fermented and unfermented). Recently, technologies for various processing treatments, such as milling, malting, blanching, acid treatment, dry heating and fermentation, which reduce antinutritional factors and increase the digestibility and shelf life of various alternative food products such as unleavened flat bread (*roti/chapati*), porridges, noodles, bakery products and extruded and weaning food products, have been developed and tested at the laboratory scale.

Pearl millet is gluten-free and, hence, has a good chance of being commercialized for the food-based management of this problem owing to its low-glycemic index; pearl millet offers unique food for diabetic patients (Table 8.5). Pearl millet is rich in oil, and linoleic acid accounts for 4 % of the total fatty acids in this oil, giving it a higher percentage of *n*-3 fatty acids as compared to maize in which linoleic acid accounts for only 0.9 % of the total fatty acids

Table 8.5 Health value of pearl millet-based diabetic products

Product	Glycemic index	
	Control (wheat flour)	Pearl millet-based products
Biscuit	72.7	58.1
Chapati	69.4	48.0
Dhokla	68.4	38.0
Instant *idli*	69.8	52.1
Pasta	71.3	54.1

Source: Mani et al. (1993)

and, hence, is highly deficient in *n*-3 fatty acids. The *n*-3 fatty acids play an important role in many physiological functions, including platelet aggregation, cholesterol accumulation and the immune system. Pearl millet in poultry feed can have a significant effect on the fatty acid composition of eggs and, consequently, on human health. In a poultry feeding trial, it was observed that eggs produced from layers fed on a pearl millet-based diet had lower *n*-6 fatty acids and higher *n*-3 fatty acids and, thus, led to lower *n*-6/*n*-3 fatty acid ratios than those fed on corn-based diets (Table 8.6). These eggs are of special health value, especially for those prone to high levels of low-density lipoproteins (LDL).

8.10 Research and Development Partnerships

Research and development are essential components of an integrated programme required to make an impact. The organizations dealing with these two components may differ in their mandate, organizational structure, operational domain and the nature and magnitude of resources, but many of them may have common goal of making an impact on the target populations and environments. It is these shared goals and ambitions to succeed that drive the research and development organization towards building the partnership and pursuing it further for its improvement, adaptation to changing conditions and successful maintenance over time. The AICPMIP has joined hands with international and national organizations broadly in three categories in pearl millet improvement research.

Table 8.6 Cereal grains and egg composition of *n*-6 and *n*-3 fatty acids

Fatty acid	Diet		
	Corn	Corn + pearl millet	Pearl millet
Diet composition of fatty acid (% of total fatty acids)			
Total *n*-6	59.3	47.0	40.0
Total *n*-3	2.4	2.5	3.3
n-6/*n*-3 ratio	25.2	19.0	12.8
Egg composition of fatty acid (mg/g yolk)			
Total *n*-6	66.8	55.6	47.3
Total *n*-3	5.1	5.5	5.7
n-6/*n*-3 ratio	13.1	10.1	8.3

Modified from Collins et al. (1997)

8.10.1 Partnership with International Research Centres

The foremost among international research centres (IRCs) is ICRISAT, which has a global mandate for pearl millet improvement, especially targeting the arid and semi-arid tropical regions of Asia and sub-Saharan Africa. Having the largest collection of more than 21,000 well-characterized germplasm accessions, ICRISAT has played a significant role in strengthening pearl millet improvement research through dissemination of large number and diverse range of breeding lines and hybrid parents. ICRISAT organizes Pearl Millet Scientists Field Day biennially and breeders from public and private sector select breeding materials of their choice (Table 8.7). ICRISAT is also involved in joint evaluation of materials in multilocational trials, generation of strategic research information and building research capacity through training. These activities are largely undertaken under the umbrella of ICAR-ICRISAT research partnership projects.

Table 8.7 Pearl millet breeding lines selected and seed samples supplied from the Scientists Field Day Selections at ICRISAT, Patancheru, India

Description	Field day year	Public	Private	Total
Number of participants	2012	22	38	60
	2014	31	38	69
Number of lines selected	2012	712	2484	2782
	2014	1302	1668	2523
Number of samples supplied	2012	1304	4941	6245
	2014	2677	1339	4016

8.11 Crop Management

Agronomic research conducted in AICPMIP included both the research station experiments and farm-level extension trials and has led to the establishment of detailed recommendations for specific/individual pearl millet growing zones with respect to the time of sowing, seed rate, weed management, fertilizer application including bio-fertilizers, intercropping, cropping sequence/rotation systems and moisture conservation techniques. This has been reviewed by several workers (Singh 1985; De and Gautam 1987; Bhatnagar et al. 1998).

Agronomic research in pearl millet can be divided in two broad areas: (1) intensive management in areas where moisture is generally adequate and (2) low-input management in areas where moisture is the major production constraint. Intensive management focuses on the increased plant population (1,75,000–2,20,000 plants/ha) achieved by maintaining 45 cm distance between the rows and 10–15 cm between plants within rows and high nutrient application. However, a lower plant population of 1,20,000/ha should be maintained in drier zones with rainfall <400 mm. Response to applied inorganic nitrogen fertilizer as high as 90–140 kg/ha has been reported from experimental trials in high rainfall areas, but farmer recommendations are in the range of generally 40–80 kg/ha in various agro-climatic zones. Inoculation of seed with *bio-fertilizers* has been reported to improve the availability of nitrogen and phosphorus to the extent of 10–20 kg/ha. The recommended dose of phosphorous for pearl millet is 20–40 kg/ha. Though weed management by chemical means has been standardized but has found little application on farmers' field. Applying atrazine at 0.5 kg/ha as pre-emergence combined with one hand weeding has also given good results.

Agronomic research for low-input arid areas has focused mainly on cropping system with legumes and on the moisture conservation techniques as pearl millet in drier areas is traditionally grown in mixture or in rotation with legumes and pulses to obtain stability in production and maintain soil fertility. Most suitable cropping systems have been worked out for diverse regions. Conservation of moisture through various techniques forms an important recommendation in dry regions. These techniques include wide-spaced crop and the use of mulch either through manipulating top soil or by organic means and to grow short duration cultivars to avoid moisture-stress situation. Though, adoptions of agronomic recommendations are mainly confined to better rainfall/assured moisture available areas, but the need to adopt improved agronomic practices is more in drier pearl millet growing areas to sustain the productivity. There exists a considerable potential for further adoption of modern inputs mainly nitrogen fertilizer and new cultivars in drier areas.

8.12 Adoption of Improved Technologies and Impact

Following the adoption of high-yielding and disease-resistant cultivars and production technology, pearl millet productivity has been consistently increasing since 1986. During the last 25 years, the productivity has gone up from 539 kg/ha during 1986–1990 to 1198 kg/ha during 2012–2013 registering a 73 % improvement, which is highest among all food crops (Table 8.8). The extent of improvement in pearl millet productivity has resulted in 45 % increase in its grain production from 5.83 million tons to 8.74 million tons, in spite of 18 % decline in crop area from 10.7 million ha to 7.3 million ha.

Table 8.8 Five-year means for grain yield and percent improvement in yield over average yield of 1986–1990 of principal food crops in India during 1986–2010

Period	Grain yield (kg/ha)					Improvement (%) in yield over average yield of 1986–1990				
	Rice	Wheat	Sorghum	Maize	Pearl millet	Rice	Wheat	Sorghum	Maize	Pearl millet
1986–1990	1622	2113	744	1371	539	–	–	–	–	–
1991–1995	1818	2429	827	1564	620	12	15	11	14	15
1996–2000	1918	2648	825	1768	733	18	25	10	29	36
2001–2005	1997	2661	784	1913	856	23	26	5	40	59
2006–2010	2161	2812	962	2124	932	33	33	29	55	73

Source: DAC, Government of India as on 7 February, 2010 available at http://www.agricrop.nic.in

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