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Genetic Resources of Pearl Millet: Status and Utilization

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Pearl millet is a very important crop of arid and semi-arid regions in Asia and Africa where it is the basis of food security of millions of people inhabiting in harsh and environmentally fragile ecosystem. Genetic resources of pearl millet including landraces, improved elite material, traditional cultivars, genetic stocks and wild relatives are very rich and, therefore, their characterization, documentation, conservation and distribution is very essential to ensure utilization in breeding programmes. This review assesses the status of pearl millet genetic resources, and identifies the gaps in their collection, conservation and utilization. A total of 56,580 accessions (including possible duplicates) of pearl millet in 70 genebanks of 46 countries across world are available. Landraces represent the largest part of pearl millet germplasm, followed by breeding/research material and wild relatives. The Indian national collection includes 7,059 accessions at the National Bureau of Plant Genetic Resources (NBPGR), New Delhi. Global collections managed by ICRISAT comprise of 22,888 pearl millet accessions from 51 countries. However, only a very small fraction of these accessions has been utilized so far. Critical assessment of collection for geographical and trait-diversity gaps using various GIS tools revealed several gaps in germplasm collection from Asian and African continents. Almost all cultivated accessions have been characterized for 23 morpho-agronomic characters following prescribed pearl millet descriptors. A large variation exists for phenotypic and phenological traits among available germplasm. In general, Indian pearl millet landraces have mainly contributed for earliness, high tillering, high harvest index and local adaptation; whereas African material has been a good source of bigger panicles, large seed size, and disease resistance. Systematic evaluation and screening of germplasm has led to the identification of specific sources of better grain quality, resistance to diseases and tolerance to abiotic stresses like drought and heat. These germplasm sources continue to play a critical role in crop improvement programmes across the world. Formation of trait-specific gene pools, core and minicore collections are likely to enhance the utilization of genetic resources to a greater degree. Strategies for further enriching the germplasm and increasing its use are discussed.

Key Words: Diversity, Genetic resources, Germplasm, Pearl millet

Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.], a diploid species (2n=14) and member of Poaceae family, is world's 6th most important food crop after wheat, rice, maize, barley and sorghum. It is grown over 30 million ha mostly in Sub-Saharan Africa and Southern Asia with a production of ~31-32 m tons (Yadav and Rai, 2013). Pearl millet is mainly cultivated in India and Pakistan in Asia; Niger, Nigeria, Burkina Faso, Sudan, Mali and Senegal in Africa; in South-Eastern USA and Australia.

Pearl millet is an important crop because of its ability to grow in severely water-limited environments and on less fertile soils with minimum inputs and thus forms the basis of food security of millions of people in the world's most harsh and fragile arid- and semi-arid regions. In addition, stover of pearl millet forms the major ration for bovines during dry and lean periods in crop-livestock production system in South Asia. Further, pearl millet is also valued as green forage in South-Eastern America, Australia, and Brazil. Pearl millet is nutritionally rich crop with high iron and zinc contents (Rai *et al*., 1997) and good calcium and lipids (Klopfenstein and Hoseney, 1995) in its grain.

Genetic variability is a bed-rock on which success of crop improvement programmes depends. Plant genetic resources are a heritage and have to be conserved for their use in future in order to achieve sustainable development and to meet challenges in achieving food security requirements. Therefore, collection, conservation, characterization, evaluation, documentation, , distribution and utilization of plant genetic resources is very essential to ensure that breeders have access to genetic resources which could be useful in breeding programmes. A large

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number of germplasm accessions are conserved at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India (Upadhyaya *et al*., 2012a,b) and at Niamey, Niger (Hay *et al*., 2013). Additionally, the ICAR-National Bureau of Plant Genetic Resources (NPBGR), New Delhi, India, has a large collection of exotic and indigenous material (Radhamani *et al*., 2011). These include wild relatives, improved elite material and genetic stocks that are potential sources of specific phenotypic traits, resistance to diseases and insect-pests; and tolerance to various abiotic stresses like drought and high temperature.

Genetic resources of pearl millet are more vulnerable to genetic erosion given that hybrids are the most dominant form of commercial cultivars. Therefore, conservation of immensely valuable material is imperative in form of trait-specific gene pools, core/mini-core collections and composites that facilitate better utilization of germplasm (Appa Rao *et al*., 1998, Singh and Jika, 1988, Upadhyaya *et al*., 2011). Some of them have been strategically utilized. The purpose of this review is to assess status of collection, conservation and utilization of germplasm in pearl millet improvement and to identify the gaps in the collection and its utilization. Attempt has also been made to further explore the possibility of enhanced use of germplasm in future breeding programmes.

Status of Pearl Millet Genetic Resources

Conservation

Global Collections: The global germplasm collections include 7.4 million accessions of various crops conserved in more than 1,750 genebanks including 56,580 accessions of pearl millet in 70 genebanks of 46 countries (FAO, 2010). Landraces represent 88% of pearl millet germplasm conserved in genebanks worldwide. About 3.2% are wild relatives, 0.8% are improved varieties, 6% are breeding/research materials and 2% are of unknown description (Mathur, 2012). In addition to the largest collection of pearl millet germplasm at ICRISAT genebank (22,288), other collections are 3,968 accessions at the Institute of Research for Development (IRD, France) from 16 countries, 3,821 accessions at the Canadian Genetic Resources Programme, Saskatoon, Canada including 3,390 accessions of cultivated pearl millet and *P. violaceum* (221), *P. macrourum* (1), *P. purpureum* (12), *P. orientale* (1), *P. pedicellatum* (11), *P. polystachion* (8), *P. ramosum* (3), *P. unisetum* (1) and other species (14) (Mathur, 2012). All collections from central African countries, were obtained through agreement with Bioversity International and Canada to conserve as duplicate collection (with the original at ORSTOM – IDR, France). The Agricultural Research Station of the USDA Griffin, Georgia is maintaining 1,314 accessions (Mathur, 2012).

The Indian national collection includes 7,268 accessions of pearl millet conserved at the NBPGR, New Delhi. Pakistan reported to have 193 accessions of pearl millet collections. Among African countries the collections have been reported from genebanks based in Algeria, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Eritrea, Ethiopia, Ghana, Kenya, Lebanon, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Senegal, Sierra Leone, Sudan, DR Congo, Uganda, Zambia and Zimbabwe (Mathur, 2012). Some other countries reported to conserve pearl millet collections are Australia (253), Brazil (52), China (102), Germany (54), Russian Federation (406) and Lebanon (110). Most of the collections with Bioversity International supported mission have now become part of the global collection maintained at ICRISAT, USDA-ARS and ILRI. Not much information is available for any of the other national collections. The number of unique accessions is lower than the total number of accessions recorded as many of them are duplicates (Mathur, 2012)

Collections at ICRISAT: The ICRISAT has made concerted efforts to assemble pearl millet germplasm by introducing the germplasm that was already collected and conserved at different national and international institutes, universities, National Agricultural Research Systems (NARS) and by launching germplasm collection missions. The major donors include: Institute Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM) (2,178), Rockefeller Foundation, New Delhi, India (2,022) and (the then) International Board for Plant Genetic Resources (IBPGR-now Bioversity International), Rome, Italy (974). ICRISAT had launched 76 collecting missions exclusively for pearl millet germplasm in 28 countries and collected 10,830 pearl millet accessions. As of now, the global collections managed by ICRISAT, Patancheru, India, comprises a total of 22,888 pearl millet accessions including 19,696 landraces, 129 improved cultivars and 2,269 breeding/research materials and 794 wild accessions from 50 countries (Table 1).

At ICRISAT genebank, about 400 g seeds each of all accessions are conserved in medium-term store maintained at 4ºC and about 30% RH (active collection) (Upadhyaya and Gowda, 2009). About 75 g each of 17,670 accessions are conserved on long-term store basis, vacuum packed in aluminum foils, which is maintained at –20ºC (base collection). Species that do not produce seed (*e.g. P. purpureum*, *P. macrourum*, *P. lanatum*, *P. squamulatum*) are maintained as live plants. Limited quantity of seeds of almost all accessions is available free of cost under Standard Material Transfer Agreement (SMTA) (Upadhyaya and Gowda, 2009) for research and training purposes.

Collections at NBPGR: Total number of pearl millet accessions at National Genebank at NBPGR is 7,268 including indigenous collection, exotic collection, released varieties and genetic stocks. Indigenous collections are in the form of landraces, farmers' varieties and wild type from 18 states and majority of them have been made from Rajasthan (603), Andhra Pradesh (265), Gujarat (215) and Uttar Pradesh (126). A large number of accessions are also conserved with no or minimum passport data (Table 2). Exotic collections (761) are also conserved in the National Genebank at NBPGR (Fig. 1). Many collections were obtained from ICRISAT and therefore, some duplication of accessions is inevitable.

Safety Backup of Collections: A part of pearl millet collection is also conserved at ICRISAT regional genebank, Niamey, Niger. ICRISAT has already deposited samples of over 20,654 accessions of pearl millet germplasm as safety backup at Svalbard Global Seed Vault (SGSV), Norway.

At ICRISAT and NBPGR, pearl millet accessions are maintained in medium-term store as active collections. Accessions are regenerated when the seed viability and or the seed quantity in active collection is below the critical level (<85% viability and/or <1/4 of total quantity) (Upadhyaya and Gowda, 2009). Seed viability of active collection is tested at five years interval and that of base collection at 10 years interval. Being the cross-pollinating crop, regeneration of pearl millet germplasm accessions is expensive and involves the risk of loss of accession integrity due to foreign pollen, mechanical mixtures, genetic drifts, genetic shifts and mutations. Therefore, during regeneration, the genetic integrity is maintained by cluster bagging method of pollination control for landraces, selfing for genetic stocks and sibbing for

Table 1. Geographical distribution of pearl millet germplasm assembled at ICRISAT genebank, Patancheru, India

Country	Breeding material + advanced cultivars*	Landraces	Wild	Total
Algeria		5		5
Australia	8			8
Benin		46		46
Botswana		82		82
Brazil	2			2
Burkina Faso	1	859	7	867
C. African Rep.		142	10	152
Cameroon	2	909	85	996
Cape Verde	2			2
Chad	4	93	37	134
Congo	8			8
Ethiopia		2	1	3
France	11			11
Gambia		15		15
Germany	3			3
Ghana	5	420		425
Great Britain	31		1	32
India (ICRISAT)	1,314 (53)		3	1,370
India (NBPGR)	403 (1)	6,064	142	6,610
Kenya		98	1	99
Korea		1		1
Lebanon	108			108
Lesotho			4	4
Malawi	2	296	12	310
Maldives		1		1
Mali	8	1,084	109	1,201
Mauritania	1	5	31	37
Mexico	10		1	11
Morocco		4		4
Mozambique		31	2	33
Myanmar		10		10
Namibia		1,118	10	1,128
Niger	57 (75)	1,617	176	1,925
Nigeria	35	2,030	9	2,074
Pakistan	10	158	2	170
Russia and CISs	12	3		15
Sierra Leone		59	1	60
Somalia		4		4
South Africa	10	152	3	165
Sri Lanka			2	2
Sudan		1,014	27	1,041
Tanzania		478	47	525
Togo		520		520
Tunisia		6		6
Turkey		2		2
Uganda	26	112	23	161
USA	177	42	10	229
Yemen		290	3	293
Zaire		11	3	14
Zambia		155	7	162
Zimbabwe	2	1,382	13	1,397
Total	2,269 (129)	19,696	794	22,888

*Figures in parentheses indicate number of advanced cultivars available in each country

male sterile lines. In cluster bagging method, panicles from 2-4 adjacent plants in a row are covered in one parchment paper bag. This allows some cross-pollination between plants of the same accession to overcome the problem of inbreeding depression caused if individual plants are selfed. Cluster bagging method is cost-effective to regenerate more accessions in a season. Pearl millet germplasm regeneration is carried out during the post-rainy season. To minimize the genetic drifts, a sample size of about 160 plants are grown in 4 rows of 4 m long each with a spacing of 75 cm between rows and 10 cm between plants.

Geographic Representation and Gaps in Collection: The collection at ICRISAT genebank represents the major diversity centres of pearl millet in Africa and Asia (Table 1). India is the major contributor of pearl millet germplasm with 6,610 accessions in Asia. Nigeria (2,074), Niger (1,925), Zimbabwe (1,397), Mali (1,201), Namibia (1,128), and Sudan (1,041) were the major contributing countries in Africa. The wild relatives' collection is from 29 countries.

Though the pearl millet collections at ICRISAT genebank is large and impressive, critical assessment for geographical and trait-diversity gaps revealed several gaps. Gap analysis, using GIS tools such as FloraMap, DivaGIS, ArcGIS etc. and passport and characterization data of pearl millet collection at ICRISAT genebank has provided opportunities to identify geographical gaps, trait-diversity and taxonomic gaps in the collection. Gap analysis using 6,434 geo-referenced pearl millet landraces originating in West and Central African countries revealed 62 districts in 13 provinces of Nigeria, 50 districts in 16 provinces of Burkina Faso, 9 districts in 6 provinces each of Mali and Mauritania, 8 districts in 8 provinces of Chad and 7 districts in 3 provinces of Ghana as the major geographical gaps in pearl millet

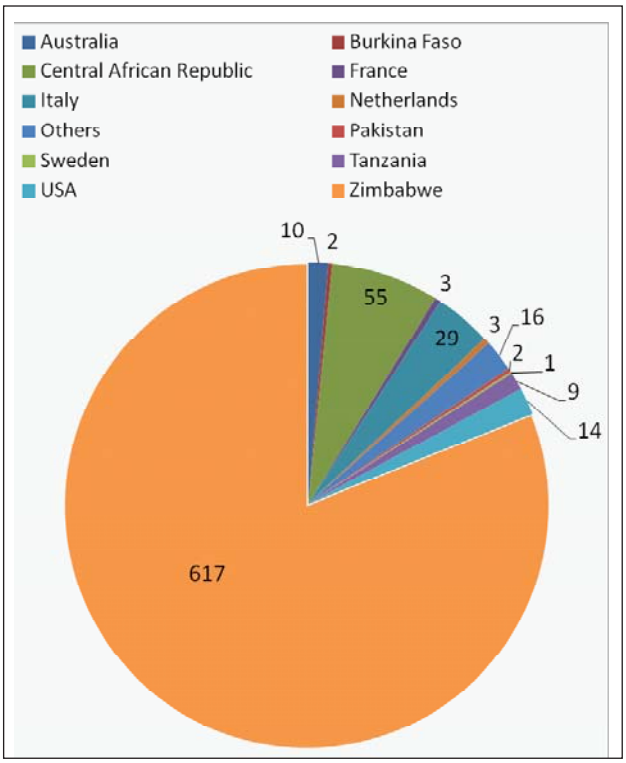

Fig. 1. Details of pearl millet germplasm from different countries conserved in NBPGR genebank, India

Table 2. Details of pearl millet germplasm from different states of India conserved in the NBPGR genebank

State	Breeding lines	Improved cultivars	Landraces	Others	Total
Andhra Pradesh	34	33	149	49	265
Bihar			1	3	4
Delhi		5			5
Goa				24	24
Gujarat	15	51	130	19	215
Haryana	7	18	39	21	85
Himachal Pradesh				9	9
Jammu and Kashmir		1	9	3	13
Karnataka		1	38	4	43
Madhya Pradesh		8	19	31	58
Maharashtra	1	10	39	15	65
Mizoram				2	2
Odisha		1	3	2	6
Punjab	7	7	73		87
Rajasthan	10	92	247	254	603
Tamil Nadu	5	7	47	30	89
Telangana	8	5			13
Uttar Pradesh	6	5	55	60	126
Other	274	16	4,459	807	5,556
Total	367	260	5,308	1,333	7,268

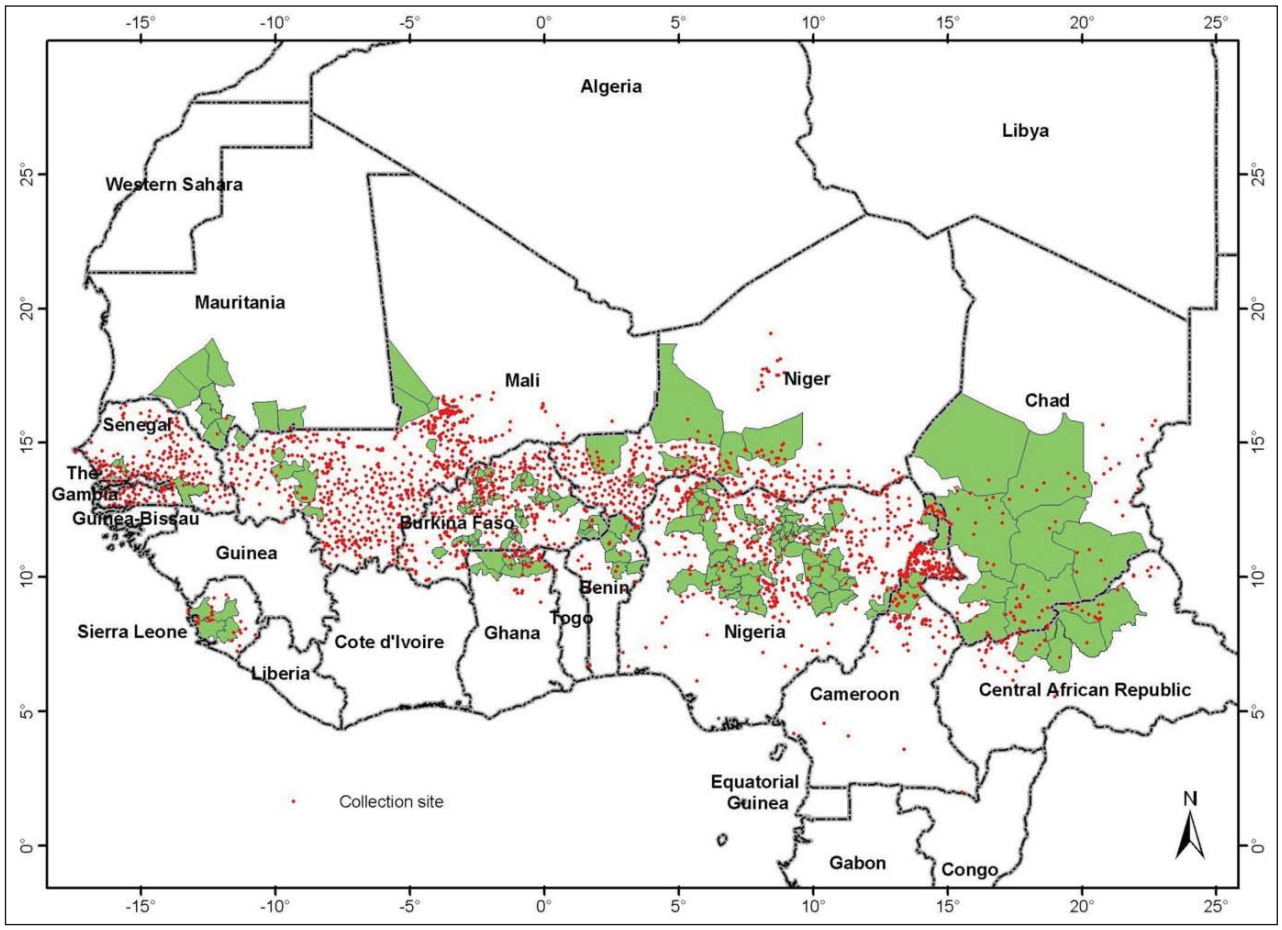

Fig. 2. Geographical gaps (districts shaded) identified in the pearl millet germplasm from West and Central African countries and collection sites (dots) of germplasm conserved at the ICRISAT genebank, India

collection from the region (Upadhyaya *et al*., 2009a) (Fig. 2). Gap analysis using 3,750 geo-referenced pearl millet landraces from East and Southern Africa revealed 34 districts located in 18 provinces of four East African countries and 76 districts located in 34 provinces of seven Southern African countries were identified as geographical gaps (Upadhyaya *et al*., 2012a) (Fig. 3).

Gap analysis of the collection at ICRISAT genebank represented by 5,768 landraces from India, Pakistan and Yemen in Asia revealed a total of 134 districts located in 14 provinces in India and 12 districts of Punjab province in Pakistan as the major geographical gaps in the collection (Upadhyaya *et al*., 2010) (Fig. 4 and 5). Beed, Latur and Osmanabad in Maharashtra in India for all traits; Rajanpur, Muzaffarpur, Multan and Lodhran for panicle length and Chakwal and Sargodha for panicle thickness in Pakistan and Southern parts of Northern province and Lahiz province in Yemen were identified as gaps for trait-diversity. Gap analysis using 335 accessions of pearl millet progenitor (*Pennisetum monodii*) revealed 354 districts located in 86 provinces of eight countries in the primary center of diversity for pearl millet including most of the West and Central African countries, as geographical gaps (Upadhyaya *et al*., 2014a). When assessed for agro-ecological pattern of diversity among 5,197 pearl millet landraces collected from 20 agro-ecological regions in India, it became clear that Malwa and Bundelkhand regions are under-represented in genebank and should be explored further for additional diversity (Upadhyaya *et al*., 2007b). The mean values and the frequency distribution suggest further exploration in agro-ecological region 3 for tall plant height, region 5 for short plant height, region 6 for high panicle exsertion and large seeds, region 8 for high number of reproductive tillers, region 10 for long panicles, region 11 for thick panicles, region 12 for late flowering and high tillering and region 14 for early flowering (Upadhyaya *et al*., 2007b).

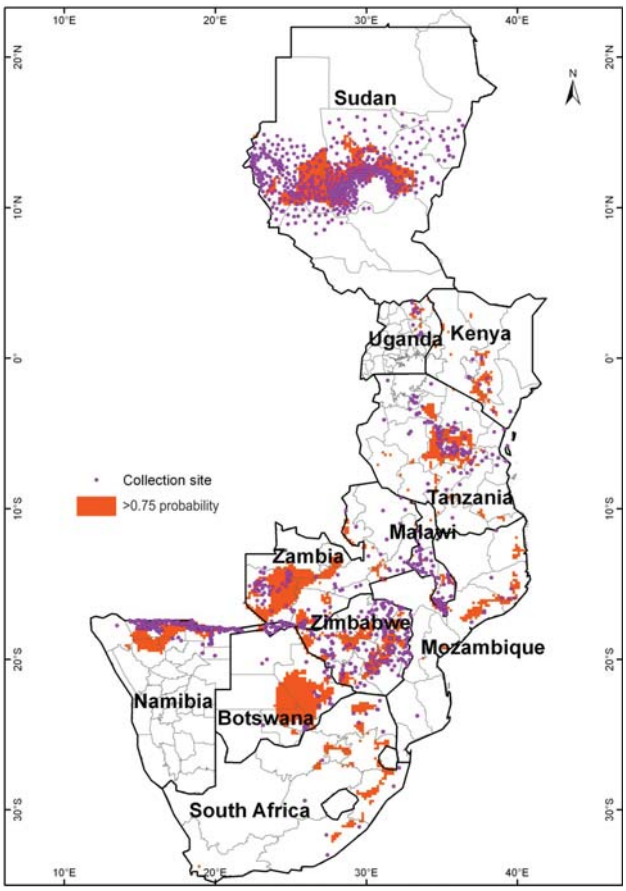

Fig. 3. Geographical gaps (districts shaded) identified in the pearl millet germplasm from East and Southern African countries and collection sites (dots) of germplasm conserved at the ICRISAT genebank, India

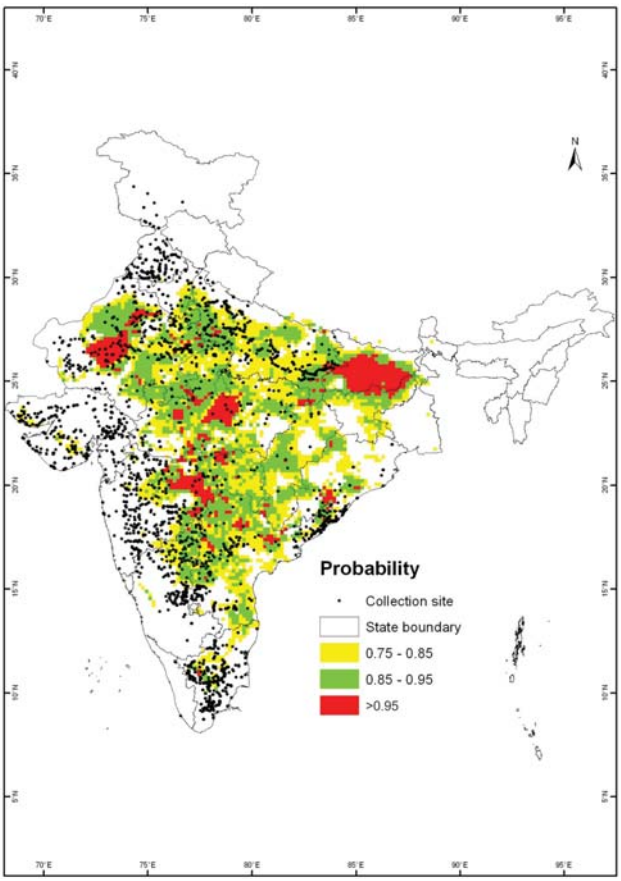

Fig. 4. Geographical gaps (districts shaded) identified in the pearl millet germplasm from India and collection sites (dots) of germplasm conserved at the ICRISAT genebank, India

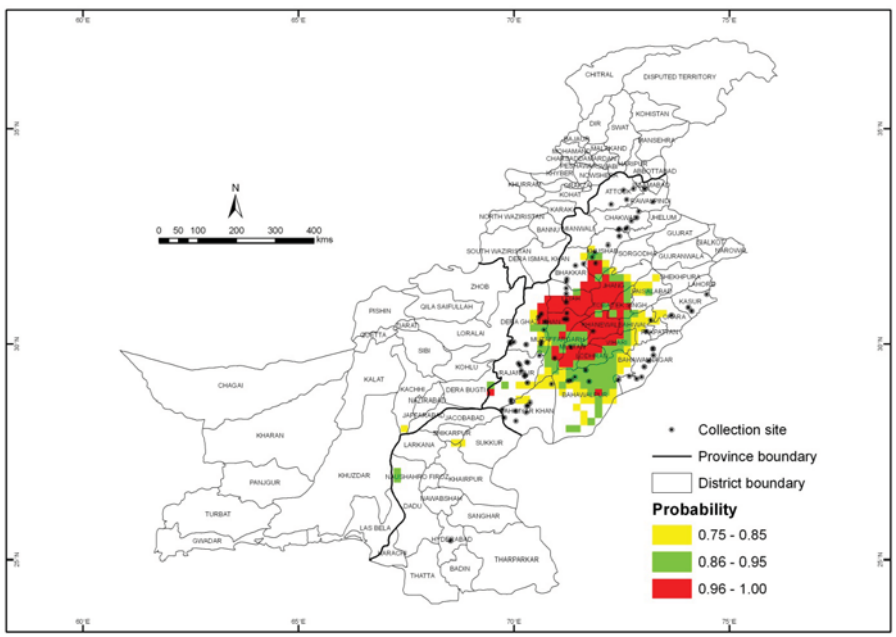

Fig. 5. Geographical gaps (districts shaded) identified in pearl millet germplasm from Pakistan and collection sites (dots) of germplasm conserved at the ICRISAT genebank, India

Characterization and Evaluation

Characterization and evaluation are pre-requisite for the efficient utilization of conserved germplasm. The world collection of pearl millet germplasm maintained at ICRISAT was characterized in batches of 500-1000 every year at ICRISAT farm, Patancheru, in alfisols during rainy and post-rainy seasons from 1974 through 2015. Rainy season crop was raised during June to October and post-rainy season crop during November to March. Germplasm accessions were grown in an augmented block design using systematic checks, repeated for every block of 20 test accessions. Each accession was sown in two 4-m long rows. Spacing was 75 cm between rows. The seed was sown using tractor mounted four-cone planter. The crop was thinned 15-20 days after sowing to give approximately 10 cm spacing between plants within a row. Lifesaving irrigations were provided in the rainy season, but irrigation was provided at regular intervals during the post-rainy season. Fertilizers were applied at the rate of 100 kg/ha N and 40 kg/ha P_2O_5 in both the seasons (Upadhyaya and Gowda, 2009).

By the end of 2015, almost all cultivated accessions were characterized for 23 morpho-agronomic characters following the descriptors for pearl millet (IBPGR and ICRISAT, 1993). Days to 50% flowering, plant height, panicle length and thickness were recorded during both rainy and post-rainy seasons, whereas number of nodal, productive and total tillers per plant, panicle exsertion, synchrony of panicle maturity, panicle shape, spikelet density, bristle length, grain yield potential, fodder yield potential and overall plant aspect was recorded only during the rainy season. Synchrony of panicle maturity, spikelet density, bristle length, grain yield potential, fodder yield potential and overall plant aspect was visually scored on a 1 to 9 scale, where 1 is most undesirable and 9 most desirable. Observations on grain characters, such as 1000-seed weight, seed shape, seed color and endosperm texture were recorded during the post-rainy season after harvesting.

Further evaluation or screening of germplasm was done by specialists such as pathologists, entomologists, physiologists, biochemists *etc*. Data obtained were added to the characterization database. Accessions/ genotypes identified with useful traits were registered as genetic stocks by assigning new accession number for conservation and utilization. To realize the true potential of the accessions and to facilitate the selection of genotypes by researchers, sets of selected pearl millet germplasm were evaluated for important agronomic characters at different locations in India and several other countries in Africa. Germplasm catalogs were prepared using the multilocation evaluation data (Mathur *et al.*, 1993). To accomplish complete characterization and evaluation of accessions, a multi-disciplinary approach was followed at NBPGR and ICRISAT and the data generated in various disciplines were added to the pearl millet germplasm databases that are being maintained in the genebank.

Diversity in Collections: Large phenotypic diversity was observed in the pearl millet collection at ICRISAT genebank for several characters. There are accessions in the collection, which can flower as early as in 33 days and as late as in 159 days in rainy season (Table 3). Similarly, plant height ranged from 30 cm to 490 cm with a mean of 249 cm. Total tillers varied from 1 to 35. Panicle size and shape are the other important traits for which diversity was very high (Fig. 6). The 1000-seed weight varied from 1.5-21.3 g. Distribution of qualitative traits indicates occurrence of nine panicle shapes, five seed shapes and 10 seed colors in the entire collection. Considerable variability for several other traits like sweet stalks, leaf traits, high seed protein content, midrib colour, dwarfism, sources of cytoplasmic-nuclear male sterility and yellow endosperm were also observed in the collection. The Shannon-Weaver (Shannon and Weaver, 1949) diversity index (H′) was calculated to compare the diversity among germplasm accessions for various traits. Phenotypic diversity (H′) ranged from 0.427 (total tillers) to 0.632 (plant height in post-rainy season) for quantitative traits. Among qualitative traits, diversity was maximum for endosperm texture (H′=0.772) and minimum for bristle length (H′=0.443). Diversity

Table 3. Range of variation in pearl millet collection at ICRISAT genebank, India

Character	Range	Mean
Time to 50% flowering-R (days)	33-159	72.7
Time to 50% flowering-PR (days)	32 - 138	71.7
Plant height (cm)-R	30 - 490	248.5
Plant height (cm)-PR	25 - 425	161
Total tillers (No.)	1 - 35	2.7
Productive tillers (No.)	1 - 19	2.1
Panicle exsertion (cm)	-45 to 29	3.5
Panicle length (cm)-R	5 - 135	28.9
Panicle length (cm)-PR	4 - 125	25.8
Panicle width (mm)-R	8 - 58	24
Panicle width (mm)-PR	8 - 61	22.8
1000-Seed weight (g)	1.5 - 21.3	8.5

R- rainy season; PR- post-rainy season

Fig. 6. Diversity for panicle size, shape and color in the world collection of pearl millet as observed during characterization

for qualitative traits was higher (H′=0.610) than that for quantitative traits (H′=0.573). Averaged over all traits, the diversity index was 0.588.

Patterns of Diversity in the Collection: Patterns of diversity for agro-ecological regions was assessed in the collection from India. Agro-ecological region is an area of the earth's surface characterized by distinct ecological responses to macroclimate as expressed by soils, vegetation, fauna and aquatic systems. Therefore, the agro-ecological region is the land unit carved out of climatic zones. The agro-ecological regions are more homogeneous both in terms of cropping patterns and climate and thus provide a better basis for studying crop responses to climatic variations. Each climatic zone is divided in to 3-9 smaller agro-ecological regions depending on the rainfall, temperature, soils, vegetation, length of growing period etc. Division of the Indian climatic zones has resulted in three agro-ecological regions (1,2 and 3) in the arid zone, five regions (4,5,6,7 and 8) in the semi-arid zone, nine regions (9,10,11,12,13,14,15,16 and 17) in the sub-humid zone and three regions (18, 19 and 20) in the coastal zone (Upadhyaya *et al*., 2007b). When assessed for agro-ecological pattern of diversity among 5,197 peal millet landraces collected from 20 agro-ecological regions in India, region 3 for tall plant height, region 5 for short plant height, region 6 for high panicle exsertion and large seeds, region 8 for high number of reproductive tillers, region 10 for long panicles, region 11 for thick panicles, region 12 for late flowering and high tillering and region 14 for early flowering as promising regions (Upadhyaya *et al*., 2007b).

Assessing the latitudinal patterns of diversity in the world collection of pearl millet landraces maintained in ICRISAT genebank revealed Northern hemisphere as predominant source with 80% of total landraces (Upadhyaya *et al*., 2014b). The latitude ranges of 10°-15°N and 15°-20°S were found as important source regions for pearl millet. Landraces from the 5°–10°N latitude region flowered late and grew tall in the rainy and post-rainy seasons and produced more tillers, while those from 10°–15°N latitude region produced fewer tillers and had long and thick panicles with larger seeds. Landraces from 10°–15°S and 20°–25°S latitudes were good sources for long-bristled and bird-resistant types. Further, late-maturing, tall and high tillering landraces from lower-latitude regions (<20° N and S) were better sources for fodder production. Early maturing landraces producing long and thick panicles with large seeds from mid-latitude regions (10°–15°) in both hemispheres were useful for developing high-yielding cultivars. Furthermore, a study on climate data of the germplasm collection sites revealed that most accessions from latitudes ranging from 10° to 20°on both side of the equator were highly sensitive to longer photoperiod (>12.5 h) and/or lower temperature (<12°C) (Upadhyaya *et al*., 2012b). Accessions that originated at higher latitudes (>25-35°) on both the hemispheres exhibited low sensitivity to both photoperiod and low temperature. The photoperiod and temperature insensitive accessions were represented from mid-latitudes (15-20°) in both the hemispheres.

The studies on elevation pattern of diversity using 229 landraces collected in Yemen revealed high diversity in landraces from low elevations for flowering and plant height (Reddy *et al*., 2004).

Access to Collections: To ensure unrestricted access to the world community, ICRISAT has placed its germplasm collections under the auspices of the Food and Agricultural Organization (FAO) of the United Nations in 1994. As per agreement with the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), ICRISAT supplies germplasm free of cost to global research community using the Standard Material Transfer Agreement (SMTA). So far, ICRISAT has distributed over 1.4 million samples accessions of mandate crops to researchers in 148 countries including

those supplied to researchers in ICRISAT. ICRISAT genebank has restored pearl millet germplasm to India (7,488), Cameroon (922) and Sudan (594), when their national collections were lost due to natural disasters or lack of proper storage facilities. Thus, national programmes have regained access to the precious heritage that would have been lost, had it not been conserved in ICRISAT genebank. NBPGR is also maintaining a trait-based database of all accessions and small quantity of seed is supplied on request.

Documentation of Collections: Documentation of genetic resources is essential for proper conservation, management and utilization of genetic resources. At ICRISAT genebank four categories of information on each accession is being maintained using GRIN-Global software (Upadhyaya and Gowda, 2009): (i) Passport data: information related to accession identity and collection, (ii) conservation data: information on storage, monitoring and regeneration, (iii) characterization and evaluation data: information on morpho-agronomic characteristics and reaction to pests/diseases, and (iv) distribution data: information related to seed supply. Passport and characterization data can be accessed through: (i) www.germplasm.icrisat.org, (ii) www.icrisat.org and www.nbpgr.ernet.in

Utilization

Sources of Specific Traits: Germplasm collections at ICRISAT and NBPGR genebanks continue to play a major role in crop improvement programmes. Over the years, systematic evaluation of germplasm accessions available in genebanks has led to the identification of several sources of phenotypic, quality and adaptation traits, and biotic and abiotic stress resistance (Table 4). In general, Indian pearl millet landraces have mainly contributed for earliness, high tillering, high harvest index, and local adaptation (Yadav and Bidinger, 2007); whereas African material has been a good source of high head volume, large seed size, and disease resistance (Anand Kumar and Appa Rao, 1987). Several genetic stocks were used as sources of biotic and abiotic stress resistance and morphological mutants were used in academic studies.

Trait-specific Gene Pools: Harlan and de Wet (1971) suggested classifying each species including its related species by gene pools, rather than by formal taxonomy. Gene pools are created to provide researcher with the widest variability in germplasm accessions so as to sustain continual improvement over a longer period of time. Different methods have been employed for developing gene pools (Burton, 1978; Singh and Jika, 1988; Appa Rao *et al*., 1998). But choice of creation of gene pools is largely determined by traits most sought after/targeted by breeders in their breeding programmes. Most frequent requests of germplasm for specific traits from breeders world over led to creation of four gene pools of pearl millet at ICRISAT (Appa Rao *et al*., 1998). These include early gene pool (EGP) constituted from 1,143 accessions, high tillering gene pool (HTGP) from 1,093 accession, large spike gene pool (LSGP) from 804 accessions and large grain gene pool (LGGP) from 887 accessions selected from 21,000 accessions. Trait-specific populations, based on abiotic-stress-adapted landraces from India, have also been developed (Yadav and Bidinger, 2007).

While constituting a gene pool or trait-specific population, all accessions with a trait of interest are selected ignoring other traits. Experience in pearl millet indicated that gene pools have slightly narrowed phenotypic variation and obscured recessive traits (Burton, 1978; Appa Rao *et al.*, 1998; Upadhyaya *et al*., 2007a). Nonetheless, such trait-specific gene pools and populations are attractive options to most breeders as it is much easier to look for the traits in the gene

Table 4. Promising sources identified in the world collection of pearl millet at ICRISAT genebank, India

Stress/Nutritional traits	No. of accessions screened	No. of promising sources identified
Abiotic stress tolerance		
Salinity	48	32
Drought	115	8
Heat	238	6
Biotic stress resistance		
Ergot	2,752	283
Downy mildew	4,727	65
Rust	2,229	332
Smut	1,747	397
Downy mildew	534	222
Nutritional traits		
High seed protein content (>15%)	1,735	272
High seed iron content (>80 ppm)	387	41
High seed iron and zinc content (>60 ppm)	387	33
High seed zinc content (>60 ppm)	387	42
Yellow endosperm	137	2

pools and populations in which random-mating would have produced recombinants along with specific trait of interest. Trait-specific gene pools and populations can be easily distributed and used as a source population for improvement through single-plant selection, recurrent selection and mass selection.

Disease Resistance: Downy mildew caused by *Sclerospora graminicola* (Sacc.) Schroet. is the most important disease of pearl millet in Indian sub-continent and Africa. Several disease epidemics have been reported in India (Dave, 1987) and destruction of the crop in Africa has also been reported (Williams, 1984). Field evaluation of more than 3,000 germplasm accessions and stability tests across locations in India and Africa has identified several sources (ICML 12, ICML 13, ICML 14, ICML 15 and ICML 16) of high levels of downy mildew resistance (Singh *et al.*, 1990). The resistant types exhibited reduced penetration, restricted mycelial growth and complete lack of haustorial formation (Chalam *et al*., 1992). Ex-Bornu from Nigeria, 3/4 Ex-Bornu and 3/4 Hainei Kirei from Niger have contributed to downy mildew resistance (Andrews *et al*., 1985). In another study, 3,163 accessions were screened and 1,220 were found to be resistant (Singh *et al*., 1987; Mengesha *et al*., 1990). Germplasm accessions from Mali, Niger, Nigeria and Senegal were the major sources of downy mildew resistance. Upadhyaya *et al*., (2007b) have reported screening of 3,164 accessions for downy mildew reaction and identified 54 promising lines. Thakur *et al*. (2001) have reported that 863 B is resistant to three pathotypes (Patancheru, Durgapura and Jalna) and had 2-8% disease incidence against Mysore pathotype. Resistance against different downy mildew pathotypes was identified from 863 B (IP 22303), P 1449-2 (IP 21168), ICMB 90111 (IP 22319), ICMP 451 (IP 22442) and IP 18293 (Upadhyaya *et al*., 2007b). Of the 238 accessions of mini core collection, 62 exhibited resistance to two or more pathotypes of downy mildew (Sharma *et al*., 2015).

Germplasm accessions have also been rich source of resistance for other important pearl millet diseases like smut, ergot and rust (Table 4). Germplasm accessions obtained from India, Uganda, Nigeria, Lebanon and Senegal yielded six promising smut resistant lines (ICML 5, ICML 6, ICML 7, ICML 8, ICML 9, and ICML 10 (Thakur and King, 1988). Further, screening of 1,747 germplasm accessions has identified 44 smut resistant lines (<10% severity) originating from Cameroon, India, Lebanon, Uganda, Mali, Senegal, Niger, Nigeria and Togo (Thakur *et al*., 1992). Variability existed among the 106 landraces evaluated for smut in Burkina Faso; the smut infection and percent seed set varied from 0.8 – 8.4% and 7.0 – 43.9%, respectively (Wilson *et al*., 1991).

A screening effort involving 2,752 germplasm accessions obtained from 19 countries and some unknown sources did not yield any accession with acceptable level of resistance to ergot (Thakur *et al*., 1993). But, 27 accessions with low ergot susceptibility (0-10%) and >75% selfed seed set from India, Nigeria, Togo and Uganda were identified. Higher levels of ergot resistance were developed from the less susceptible lines by inter-mating and pedigree breeding. Thakur and King (1988) have registered four ergot resistant germplasm lines (ICML 1, ICML 2, ICML 3, ICML 4). Under international trials, ergot infection ranged from 1-3% among the four resistant lines. Additionally, these lines also exhibited resistance to downy mildew and smut.

Several accessions from different African countries and India were found to show 0-10% rust severity (Singh *et al*., 1997). Further, several sources of resistance to rust were identified which originated from India, Senegal, Nigeria, USA, Mali, Cameroon, Chad, and Burkina Faso. The 17 rust resistant entries identified were from Nigeria (700481-21-8, 700481-22-8, 70041-23-2), Senegal (P 1564, P 1577, P 1581, P 1591), Cameroon (P 24, P 140), Niger (D 212 P1, P 2890), Mali (IP 548, P 615), Chad (7042-1-4-4), Sudan (IP 8695-4), USA (IP 537-8) and India (IP 2084-1). Singh *et al*. (1987 & 1990) have reported some resistant germplasm accessions (ICML 11, ICML 17, ICML 18, ICML 19, ICML 20, and ICML 21) that have been registered. Three accessions (IP 7846, IP 11036 and IP 21187) have recently been reported to possess resistance to four pathotypes of blast disease (Sharma *et al.*, 2013).

Abiotic Stress Tolerance: Drought is the most important abiotic stress impacting the pearl millet production. Therefore, identifying sources of drought tolerance is very crucial for developing improved cultivars. Germplasm accessions and other genetic stocks are a very valuable source for drought tolerance and escape (Table 4). Earliness is important especially for arid regions. Murty *et al*. (1967) characterized 1,532 accessions and reported variation for days to flowering among Indian (52-77 days) and exotic (53-85 days) collections. In another study, the days to flowering showed much wider variability (33-140

days) among the world collection of 16,968 pearl millet accessions (Harinarayana *et al*., 1988). IP 4021 (Bhilodi) collected from Gujarat was earliest with 33 days to 50% flowering in rainy season and 34 days in post-rainy season. Further, screening efforts identified two promising drought tolerant lines among the 509 accessions screened (Harinarayana *et al*., 1988). Landraces identified from Rajasthan, India exhibited wide variability for different characters. SR 15, SR 17, and SR 54 were three landraces that were identified for earliness. Three other unique landraces that showed earliness were 'Chadi' from Rajasthan, 'Bhilodi' from Gujarat and 'Pittaganti' from Eastern Ghats of India (Kumar and Appa Rao, 1987). Further, germplasm accessions IP 4066, IP 9496 and IP 9426 were identified as promising early lines. In a detailed study conducted across a wide range of environmental conditions, 105 landraces were evaluated and a wide range in the drought response was observed and landraces having high degree of drought tolerance have been identified for use in developing drought tolerant cultivars (Yadav *et al*., 2003).

Salinity is another important production constraint especially in some parts of India. Genetic variability has been reported for salinity tolerance in pearl millet (Ashraf and McNeilly, 1992; Chopra and Chopra, 1997). Among the 24 accessions evaluated for salinity tolerance, KAT/PM-2 Kitui, Kitui local and 93613 produced greater dry matter (Ashraf and McNeilly, 1992). These three accessions along with 93612 had longer shoots compared to other accessions. In another study, 45 germplasm accessions (23 landraces, 18 dual-purpose lines and 4 accessions of *P. purpureum*) that included 40 accessions from Western and Central Africa, 3 from Eastern and Southern Africa and 2 from India were evaluated (Kulkarni *et al*,. 2006). Among these IP 22269 and IP 6098 were found to be promising dual purpose lines producing about 1420 kg/ha grain yield (comparable to Raj 171 – 1492 kg/ha) and about 40-60% higher dry fodder yield compared to the check variety Raj 171 (3513 kg/ha) under field trials. Further, IP 3616, IP 6105, IP 6112 and IP 6104 were found to be promising lines for dry-fodder yield. IP 22269 is 'High Tillering Gene Pool (HTGP)' collection from ICRISAT (Appa Rao *et al*., 1988), IP 3616 a dual-purpose collection from Tamil Nadu and IP 6104 and IP 6112 are from Niger (Kulkarni *et al*., 2006). Vegetative stage salinity tolerance was evaluated using 100 entries that included 35 hybrid parents, 61 population progenies, 2 OPVs and 2 germplasm accessions (Krishnamurthy *et al*., 2007). Among these HTP 94/54, ICMP 451, CZI 9621 and IP 3757 were identified to be most tolerant entries. Additionally, 863 B and ICMB 94555 were found to be moderately tolerant. Upadhyaya *et al*. (2007b) have reported 32 promising accessions identified after screening 48 accessions for salinity tolerance. A pearl millet variety 'HASHAKI 1' has been identified for release in Uzbekistan as high forage variety for salt affected areas (Yadav *et al*., 2012).

In view of climate change and rising temperatures, tolerance of crops to high temperature during their reproductive stage has recently assumed high significance. The high temperatures have relevance at both seedling and reproductive stages of crop. Several growth processes like the rate of germination, rate of coleoptile elongation, or the rate of photosynthesis require rather high optimum temperatures, *e.g*., 35°C in pearl millet, which is indicative of good adaptation of pearl millet to the hot growing conditions. Peacock *et al.* (1993) identified a few genotypes from Rajasthan for better survival under high soil surface temperatures during initial stage of development.

Large genetic variation for tolerance to heat at reproductive stage among pearl millet breeding lines and populations has also been observed, and heat-tolerant lines have been identified (Gupta *et al*., 2015). Based on multi-locational screening, five maintainer lines ICMB 92777, ICMB 05666, ICMB 00333, ICMB 02333 and ICMB were found to have more than 60% seed set when the air temperature during flowering exceeded 42˚C. Populations like ICMV 82132, MC 94, ICTP 8202 and MC- Bulk have also been identified as sources of heat tolerance for further selection. Three germplasm accessions (IP 19799, IP 19877, IP 19743) were also identified as heat tolerant (seed set of >50%), and can also be further utilized for diversifying the genetic base of heat tolerant materials in pearl millet (Yadav *et al*., 2012)

Nutritional Traits: Pearl millet is a highly nutritious crop and contributes to about 19-63% and 16–56% of total iron (Fe) and zinc (Zn) intake from all the food sources (Parthasarathy Rao *et al*., 2006). Evaluation of 297 Iniadi germplasm accessions originating from Western Africa (Togo, eastern Ghana, southern Burkina Faso and western Benin) has indicated wide

variability for Fe and Zn density levels (Rai *et al.,* 2008). Fe levels in 101 accessions were equal to or higher than the commercial OPV ICTP 8203 (81 mg/kg). Among these, 92 accessions also had Zn density greater than or equal to 61 mg/kg (ICTP 8203 – 59 mg/kg). IP 17602 (121 mg/kg), IP 17673 (109 mg/kg) and IP 9404 (108 mg/kg) were the three accession with highest levels of Fe density compared to ICTP 8203 (81 mg/kg). Similarly, Zn density levels were found to be highest in IP 17602 (87 mg/kg), IP 17561 (86 mg/kg) and IP 17836 (82 mg/kg) compared to ICTP 8203 (59 mg/kg). In another trial involving 90 entries (40 hybrid parents, 30 populations and progenies and 20 germplasm accessions), 863 B was identified to contain the high Fe levels (72.7 mg/kg) (Velu *et al*., 2007) and good amount of Zn (55.8 mg/kg) (Rai *et al*., 2008). The grain Fe density among 18 OPVs and 121 commercial hybrids has been reported to vary from 42 mg/kg to 67 mg/kg, and Zn from 37 mg/kg to 52 mg/kg (Rai *et al*., 2016).

Additionally, 260 promising accessions for high seed protein content (>15%) have been identified among the 1,270 accessions (Upadhyaya *et al.*, 2007b). Further, wide variation for grain protein content was identified among the pearl millet genotypes from Sahelian West Africa (Buerkert *et al.,* 2001). Additionally, among the 22 landraces, 22 improved varieties, 6 inbred X variety hybrids (IVHs) and 4 top-cross hybrids (TCHs), landraces outperformed the varieties, IVHs and TCHs. Further, wide variability for crude protein content (9.71-15.43%) was also observed among the 61 local pearl millet accessions from Tamil Nadu, India (Govindraj *et al*., 2011).

Efforts are being made at global level to enhance the pearl millet nutrition including micronutrients to overcome malnutrition. The protein content in pearl millet mini core accessions ranged from 6 to 13%, averaged 10.7%. IP# 3642, 4291, 4363, 4488, 4747, 9198, 12431, 13624, 13636, 16489, 17465, and 19877 had 9-18% greater protein content than the control, IP 3616 (11%), with IP 3642 and IP 19877 having the highest protein content 13%. The genetic variation for grain Fe and Zn in mini core collection ranged from 34 to 95 ppm, averaged 69 ppm, for Fe, while from 29 to 81 ppm, and averaged 56 ppm, for Zn content. IP# 4363, 4747, 9198, 12431, 13624, 13636, and 19877 had 9-11% greater Fe (86-88 ppm) than best control (IP 17862). Likewise, accessions with 11-25% greater Zn than IP 17862 were IP# 4177, 4291, 4363, 4488, 4747, 9198, 12431, 13624, 13636, and 17465. Six of these accessions (IP# 4363, 4747, 9198, 12431, 13624, and 13636) had both high grain Fe and Zn. The control IP 17862 had 79 ppm Fe and 63 ppm Zn. The wild relatives are useful sources for various nutritional traits. In a preliminary study at ICRISAT, 101 accessions of *P. violaceum* had combination of protein, iron and zinc higher than the best controls. The research is in progress to identify stable sources to develop nutrient dense broad based open pollinated and hybrid cultivars. Seed quality traits are highly influenced by environment and genotype by environment interaction, therefore, necessitating the need for further evaluation to identify nutrient dense germplasm.

Direct Use in Cultivar Development: The use of germplasm in pearl millet improvement programmes in national and international research institutes has resulted in the release of commercial cultivars in different countries. Mass selection in locally adapted germplasm has been used extensively in cultivar development. Varieties like Co 1, Co 2, Co 3, Co 4, Co5, Jakharana, RSJ, RSK, Pusa Moti and S530 were developed in 1960s and 1970s (Yadav and Rai, 2013). While Co 1, Pusa Moti and S 530 were developed from African material (Harinarayana and Rai, 1989) the others were developed from Indian landraces. Later WC-C 75 and ICMS 7703 were developed from intercrossing of African and Indian material. Similarly, RCB 2 was developed from selections among the Indian landraces from Rajasthan. Development of ICTP 8203, a high yielding, downy mildew resistant and large-seeded variety was developed through direct selection within large-seeded Iniadi landrace from northern Togo (Rai *et al*., 1990). This same variety was released as Okashana 1 in Namibia and as Nyankhombo (ICMV 88908) in Malawi (Upadhyaya *et al*., 2007a). Even prior to the release of Okashana 1 in Namibia, the Iniadi-type material was available as Serere 17 (Tanzania) and Serere 6A (Botswana) in southern and eastern Africa (Andrews and Kumar, 1996). Improved version of ICTP 8203 containing higher Fe content in its grains has recently been released as Dhanshakti (Rai *et al*., 2014).

Okashana 2, a variety was developed from a cross involving Zimbabwe local landrace IP 16504 with ICCMV 87901 and ICMV 88908 and released in Namibia in 1998 (Obilana *et al*., 1997). Further, two other OPVs (ICMV 221 and RCB-IC 911) were developed from bold

seeded composite (BSEC) (Andrews and Kumar, 1996). The 'Iniadi' landrace has also been utilized in developing CZP-IC 923, which was a collaborative effort involving ICAR-CAZRI, Jodhpur and ICRISAT, India. CZP 9802, another OPV was developed from early maturing and high yielding progenies of a population from Rajasthan, India (Yadav, 2004). The varieties JBV 2 and JBV 3 were developed from Early Composite 91 and SRC II, respectively. Two other varieties *viz*., HC 10 and ICMV 155 were developed from early maturing and drought tolerant 'New Elite Composite (NELC)'.

Local landraces *per se* have been put to relatively greater direct use in western Africa for developing open pollinated varieties (OPVs). IKMP 1, a variety was developed and released in Burkina Faso by recombining selections made from landraces. Further, two varieties IKMP 3 and IKMP 5 were developed as selections from landraces CVP 417 and CVP 170, respectively (both from Burkina Faso; Upadhyaya *et al*., 2007a). Similarly, an OPV ICMV-IS 88102 was developed as selection from a landrace IP 6426 and released in Burkina Faso and Mali. Another variety, Kangara was developed from two landraces and white grain composite and released in Namibia during 1998. Kangara was also released in Zimbabwe as PMV 3 (Obilana *et al*., 1997). Several cultivars (IKMV 8108, IKMV 8109, ICMV IS 91106, and ICMV IS 91108) were developed from the Iniadi material for the west and central Africa (Andrews and Kumar, 1996). Additionally, another OPV, GB 8735 was developed from cross involving Iniadi and Souna (early maturing landrace from Mali) landraces (Andrews and Kumar, 1996). This OPV was tested and released for cultivation in Mauritania, Chad and Benin.

A significant impact of germplasm use has been on hybrid development. The male-sterile line Tift 23A was introduced in India from USA in 1962. HB 3 was a popular hybrid that was developed using Tift 23 A (seed parent) and J 104 (pollen parent). J 104 was derived from Indian germplasm material. BJ 104, and CJ 104 were two other hybrids that were developed using 5141A, bred from Indian germplasm. Three hybrids (BK 560, GHB 27 and GHB 32) were all developed using 5141A as seed parent. The pollen parents for these three hybrids were K560-230, J 2002 and J 1188, respectively and these were all developed from Indian germplasm. The pollen parent of ICMH 451 (ICMP 451) and ICMH 423 (ICMP 423) were derived from late and early composites, respectively. The pollen parent (H 77/833-2) of highly popular and early maturing hybrid HHB 67 was selected from a Rajasthan landrace. Additionally, several hybrids based on 'GHB' series were developed using pollen parents that were derived from Indian germplasm. Further, two MS lines ($L66A_2$; $L67A_3$) were developed from African germplasm at Punjab Agricultural University, Ludhiana, India. Two more male-sterile lines *i.e.* CZMS 44A and CZMS 47A were developed at CAZRI, Jodhpur using local germplasm material collected from Barmer, Rajasthan, India (Manga and Yadav, 1997).

'Iniadi' or 'Togo' population has been utilized in developing hybrid parents (male-sterile lines and restorers) that have been used in hybrid development. Several of the early-maturing hybrids developed in India are based on male-sterile lines derived from Iniadi material collected from Ghana (Dahlberg *et al*., 1997). A high yielding downy mildew resistant hybrid (ICMH 312) was developed from a cross involving ICMR 312, a restorer population developed from BSEC and 81 A (Andrews and Kumar, 1996). 863 A and ICMA 88004 are two male-sterile lines that have been developed from the Togo population. Further, A/B pair of 863 was developed from Iniadi landrace material. Studies conducted by SADC/ICRISAT SMIP jointly during the late 1980's and early 1990's observed heterotic vigor in crosses involving local landrace variety (LLV) accessions and improved released varieties (Monyo *et al*., 1996). The intervarietal hybrid developed from crossing SDMV 89003 (improved variety) and SDPM 626 (a LLV) produced 33.7% (3930 kg/ha) higher yield than the control variety, PMV 2 (2942 kg/ha). While the crosses involving LLVs from Tanzania demonstrated yield superiority of up to 89.8% over Serere 17.

Forming Representative Core Collections for Enhancing Utilization: With the establishment of genebanks at ICRISAT and NBPGR, the range of available pearl millet germplasm has increased tremendously. However, there are various bottlenecks to the increased use of genetic resources. The main reasons for low use of germplasm includes larger size of collections, lack of reliable data on traits of interest to the user, restricted access to the accessions, inadequate linkages between genebank and the users and limited capacity of breeding programmes to absorb new material.

To enhance germplasm utilization, core collections consisting 2,094 accessions (10% of entire collection) (Upadhyaya *et al*., 2009b), mini core collection consisting

238 accessions (10% of core or 1% of entire collection) (Upadhyaya *et al*., 2011) and reference sets of genetically most diverse accessions (Upadhyaya *et al*., 2006) were developed. Developing a core collection that represents the diversity of entire collection is an efficient approach to enhancing the use of germplasm in crop improvement (Upadhyaya *et al*., 2009b). Core collections are dynamic and need to be revised when additional germplasm and information become available. The pearl millet core collection, consisting of 1,600 accessions selected from 16,000 accessions characterized at the ICRISAT genebank up until 1998, was augmented by adding 501 accessions representing 4,717 accessions assembled and characterized later. The revised core collection consists of 2,094 accessions (five duplicate and two male-sterile accessions were deleted from the original core collection). A comparison of mean data using the Newman–Keuls test, variance using Levene's test, and distribution using $\chi 2$ test indicated that the variation in the entire collection of 20,766 cultivated accessions was preserved in the revised core collection. The Shannon-Weaver diversity index for different traits was similar in the revised core and entire collection. The revised core collection was observed to be more valuable than the original core as it has sources of resistance for important diseases including downy mildew (Upadhyaya *et al*., 2009b).

Even a core collection consisting of 2,094 accessions is large and can become too unmanageable to evaluate and characterize the accessions for economic traits. Hence, a mini-core collection of pearl millet, comprising 238 accessions was constituted following Upadhyaya and Ortiz (2001) using evaluation data of core collection accessions for 18 morpho-agronomic traits (Upadhyaya *et al*., 2011). Results indicated that almost the entire genetic variations and a majority of co-adapted gene complexes present in the core-subsets were preserved in the mini-core subsets. Due to its greatly reduced size, the mini core will serve as gateway to the entire collection of pearl millet for proper exploitation of pearl millet genetic resources for crop improvement. Molecular characterization of mini core collection and composite collection further revealed genetic usefulness of the germplasm accessions in allele mining.

Development of mini core collection (1% of total collection) representing the core and entire collection for diversity has resulted in the extensive evaluation of mini core sets and identification of several promising sources for agronomic and nutritional traits and biotic and abiotic stresses.

Using Wild Relatives: As there was large amount of genetic variability available in pearl millet landraces for useful traits, use of wild relatives in crop improvement was negligible. There have been a few targeted attempts and the results have been encouraging. For example, the use of *P. glaucum* subsp. *monodii* led to the identification of new source of cytoplasmic-nuclear male sterility, referred to as A_4 (Hanna, 1989). Hanna (1992) has summarized the use of this wild relative for new sources of resistance to leaf diseases that of *P. purpureum* for sources of forage traits, and stiff stalk and restorer genes of the A_1 CMS system, and that of *P. squamulatum* Fresen for apomictic gene (Rai *et al*. 1997). Crop wild relatives contain higher levels of resistance for both biotic and abiotic stresses and are promising for some agronomic and nutritional traits. Therefore, these will continue to play a vital role in crop improvement programmes, more so under conditions of climate change (Hanna, 1992). *P. pedicellatum and P. polystachion* are resistant to downy mildew, rust and leafspot and produce more tillers.

Future Prospects

Landraces and traditional cultivars have evolved over centuries by natural and human selection under drought, high temperature or saline conditions. They are better adapted to the local conditions and would contribute in enhancing the resilience at the farm level. Such landraces and germplasm accessions could be of immense importance especially as sources of native genes conditioning resistance to various biotic and abiotic stresses and thus would be of great help to the farming community. These could also serve as excellent genomic resource for isolation of candidate genes responsible for tolerance to climatic and edaphic stresses for accelerating further genetic improvement of pearl millet as well as for their possible deployment in the genetic improvement of other crops.

There is renewed interest in pearl millet and other coarse grain cereals as health and functional food. The assessment of pearl millet germplasm as health food has indicated a good variation in several micronutrients. Pearl millet can be a useful source for carotenoids having anti-oxidant properties and pro-vitamin A activity. Available germplasm should be searched for native variation in these traits.

Additional explorations are needed in the regions where collection gaps have been indicated. *Ex situ*

conservation of genetic resources from such regions and distribution of germplasm to the stakeholders on regular basis would remain very crucial especially in the present scenario of climate change. Like other crops, the proportion of available germplasm used in breeding programme of pearl millet has been very limited. The development of core and minicore in recent past is expected to improve this situation. Developing *e*-resources with detailed information like passport data, characterization and evaluation data with respect to individual accessions would certainly help in enhancing the utilization of genetic resources in order to broaden the genetic base of commercial cultivars which is very essential to reduce the chances of disease epidemics and to mitigate the effects of climate change.

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