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REVIEW

Crops that feed the world 11. Pearl Millet (*Pennisetum glaucum* L.): an important source of food security, nutrition and health in the arid and semi-arid tropics

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Abstract Pearl millet is a major cereal in the arid and semi-arid regions of Asia and Africa. It is primarily cultivated for grain production, but its stover is also valued as dry fodder. Pearl millet is resilient to climate change due to its inherent adaptability to drought and high temperatures. It is also tolerant of saline and acid soils, and is well adapted to marginal lands with low productivity. Pearl millet germplasm exhibits large genetic variability for yield components; and various agronomic, adaptation and nutritional traits. Open pollinated varieties and hybrids are two important cultivar options, but higher productivity is realized through hybrids. Pearl millet has fewer pest and disease problems compared to other cereals and is suited to different cropping systems. It is highly responsive to improved crop management practices, as witnessed in parts of India where it is grown as an irrigated summer crop that produces higher yields and better quality grain. Pearl millet has high nutritional value in terms of high levels of energy, dietary fibre, proteins with a balanced amino acid profile, many essential minerals, some vitamins, and antioxidants. These play a significant role in prevention of important human ailments such as diabetes, cancer, cardiovascular and neurodegenerative diseases. There is great potential for harnessing these positive attributes through genetic improvement, improved crop management, and grain processing and food products technologies. These should help to develop greater global awareness of the importance of this crop for food and nutritional security.

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Introduction

Crop species endowed with resilience to various adverse climate change effects, and having high nutritional values can make significant contributions to addressing food and nutritional security, especially in developing countries. Millets are increasingly being recognized for their high levels of resilience to climate change effects, and high nutritional properties. The term 'millet' includes many species of various genera, amongst which the more prominent are pearl millet (*Pennisetum glaucum* (L.) R. Br.), finger millet (*Eleusine coracana*. (L.) Gaertn), foxtail millet (*Setaria italica* (L.) Beauv) and proso millet (*Panicum miliaceum* L.). Segregated global data on all these millets are not available, but total global area under finger millet, foxtail millet and proso millet put together is no more than 8 million ha. In comparison, pearl millet occupies more than 30 million ha in 30 countries, spread across Asia, Africa, the Americas and Australia (Yadav et al. 2012). The two dominant regions for pearl millet cultivation are Asia, and Western and Central Africa (WCA). India is the largest producer of pearl millet, both in terms of area (~8.5 million ha) and production (~9.0 million tonnes) during 2009–10 to 2013–14 (Agriculture Statistics, GOI 2014). Average yield during this period was ~1069 kg/ha. The north and north-western parts of India are the major pearl millet growing regions, contributing >90 % of the production

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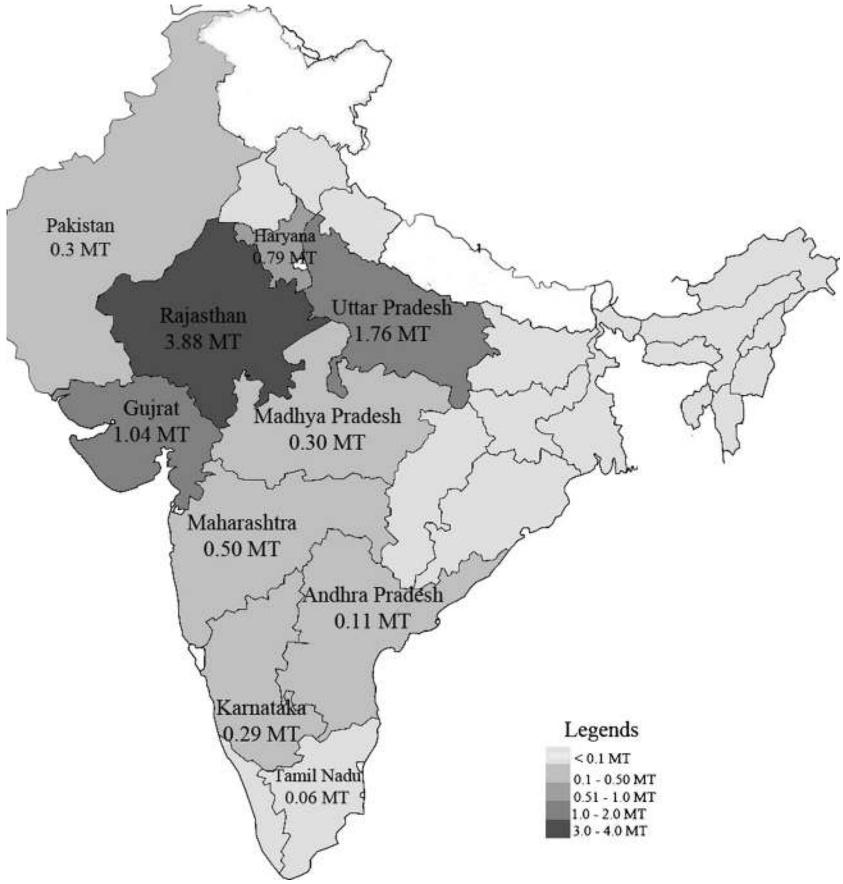


Fig. 1 Pearl millet production in different states of India during 2012–13 (MT – million tonnes). *Source*: Agricultural Statistics, GOI (2014), Ministry of Agriculture, DAC & DES, India

(Fig. 1). The regions comprising west/central Africa (WCA) and east/southern Africa (ESA) are important pearl millet production areas. In the WCA region, Nigeria, Niger, Chad, Mali and Senegal there is a considerable area under millet production (Fig. 2). Similarly the ESA countries, Sudan, Ethiopia and Tanzania, contribute significantly towards millet production. Pearl millet's production share is up to 95 % of total millet production or more in some countries of WCA and parts of ESA (Nedumaran et al. 2014).

Pearl millet is mostly cultivated for grain production in Asia and Sub-Saharan Africa, but it is also valued for stover as a source of dry fodder. In other countries, it is mostly cultivated as a forage crop. Pearl millet is a drought and heat-tolerant cereal crop that gives a stable grain and forage yield on poor, sandy soils under hot, arid and dry environments. Despite several crop production constraints in these harsh environments, pearl millet is cultivated either as a mono-crop or in intercropping and mixed cropping. The latter two practices provide greater food and financial security to smallholder farmers. Pearl millet, along with sorghum and maize, is often associated with the poorest of the poor in Sub-Saharan Africa and Asia, for whom they contribute the majority of calories for millions of people. Pearl millet is a good source of fat, vitamins and carbohydrates (Hulse et al. 1980). In comparison with other cereal crops, it is nutritionally better as it has higher levels of iron, zinc, calcium, lipids, and proteins (Klopfenstein and Hoseney 1995). But the nutritional quality of pearl millet is reduced by the presence of anti-nutritional factors such as polyphenols and phytic acid, which interfere with mineral bioavailability (Thorne et al. 1983; Carnovale et al. 1988) and also inhibit proteolytic enzymes (that catalyze hydrolysis of proteins; Knuckles et al. 1985); and amylolytic enzymes (involved in degradation of starch; Sharma et al. 1978), and thus reduce the digestibility of proteins and starch.

Globally, pearl millet is consumed in different forms: unleavened bread (roti or chapatti), porridge, gruel, and dessert; and it is often referred to as a "poor man's bread" (Burton et al. 1972). Its flour can substitute (10–20 %) for wheat flour in 'whole-grain' breads, pretzels, crackers, tortillas, dry and creamed cereals (Dahlberg et al. 2003). Though pearl millet is a staple cereal of the arid and semi-arid regions of Sub-Saharan Africa and Asia with potential nutritional and medicinal value, it has received limited attention from the scientific community and funding agencies as compared to other major cereals such as rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). This paper attempts to present the various aspects of pearl millet, including its origin and taxonomy, biology and adaptation, production constraints, crop improvement and management practices, nutritional value and various health benefits.

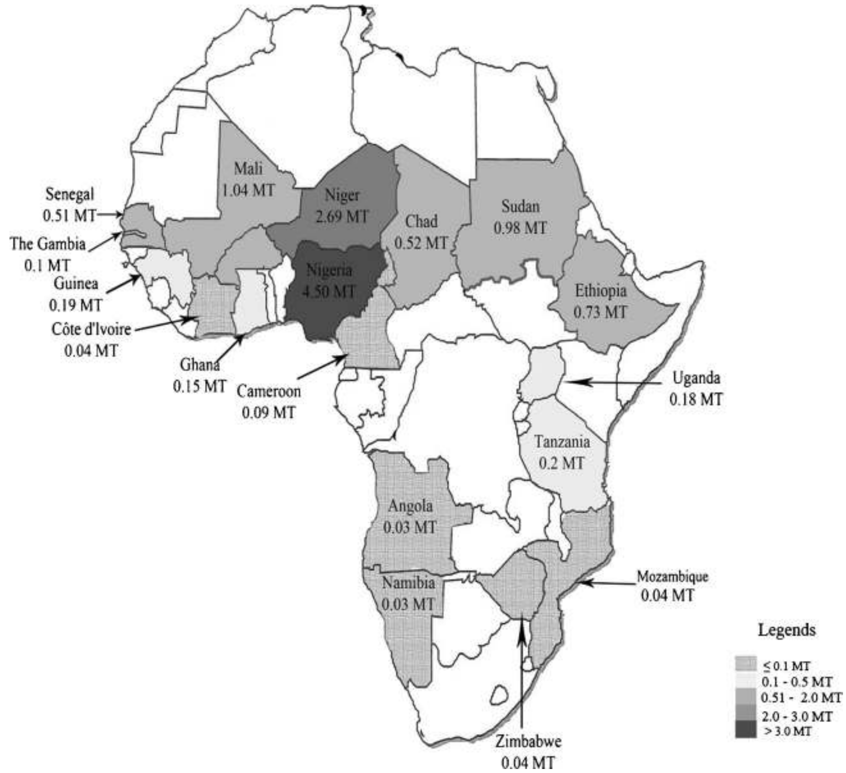


Fig. 2 Major pearl millet producing countries in Africa during 2013 (MT – million tonnes). *Source*: FAOSTAT 2015 and Nedumaran et al. 2014

Origin and history

Pearl millet is a major crop of sub-Saharan Africa, stretching from Sudan in the east to Senegal in the west, and in Asia (largely Indian sub-continent). But, there is still no clear cut understanding of the evolutionary history of pearl millet. As per the botanical evidence, *P. fallax – P. violaceum* complex could be the progenitor of the domesticated pearl millet (de Wet et al. 1992). Clayton (1972) reported the occurrence of these wild taxa across the Sahel and the central highlands of the Sahara but Harlan (1975) and Brunken (1977) have identified *P. glaucum* ssp. *Monodii* (= monodii found in the Sahel region of West Africa) to be the wild progenitor of pearl millet. Cereal cultivation had spread from the Near East to North Africa about 5000 years ago (Clark 1962) but with the advent of the dry phase in North Africa, farmers were forced to move south, abandoning the temperate cereals and starting to domesticate more favourable tropical grasses (Clark 1964). *P. glaucum* was the first grass that was domesticated along the southern borders of the expanding desert.

Archaeological evidence indicates the use of *P. glaucum* as a wild cereal along northern Ghana and the south-western fringes of the Sahara as far back as 3000 years. Race typhoides could be the oldest form of cultivated pearl millet (de Wet et al. 1992) and also the progenitor of West African cultivated races that probably reached India about 2500 years ago (Rao et al. 1963). Some researchers suggest multiple domestications (Harlan 1975; Porteres 1976) while others propose a single domestication (Marchais and Tostain 1993). Though there is disagreement over the number of domestications, many authors agree that domestication itself took place in Africa (Harlan 1975; Porteres 1976; Marchais and Tostain 1993). Again, within Africa, different regions from Mauritania to Sudan (the Sahelian zone) have been proposed as the probable centres of origin.

Taxonomy

The present taxonomical classification for pearl millet is based on Clayton (1972); but, de Wet (1977) accepted *Pennisetum glaucum* instead of *P. americanum* as annual pearl millet species. The accepted classification for pearl millet is: family – *Poaceae*; subfamily – *Panicoideae*; tribe – *Paniceae*; subtribe – *Panicinae*; section – *Panicillaria*; genus – *Pennisetum*; species – *glaucum*. *Pennisetum*, the largest genus in the *Paniceae* tribe, has five sections (*Pennicillaria*, *Gymnothria*, *Eupennisetum*, *Heterostachy* and *Brevivalvula*; Stapf and Hubbard 1934) and about 140 species (Clayton 1972). *P. glaucum* (*P. americanum* according to Brunken 1977) is divided into three sub-species: (a) *glaucum* – cultivated species; (b) *violaceum* (*monodii*) – the wild progenitor of cultivated pearl millet; and (c) *stenostachyum* - produced from natural hybridization between *glaucum* and *violaceum*.

Depending on the crossability and concept of species, *Pennisetum* has been classified into three gene pools: primary, secondary and tertiary (Hay et al. 2013). Taxa that can easily cross with cultivated pearl millet and produce fertile hybrids are included in the primary gene pool. Diploid annuals (2n = 2× = 14) included in the primary gene pool are: *P. glaucum*, its wild progenitor (*P. glaucum* subs*p. Violaceum* [= *monodii* Maire]) and weedy form (*P. glaucum* subsp. S*tenostachyum*). The taxa that can cross easily with cultivated types, but do not produce fertile hybrids are included in the secondary gene pool (*P. purpureum*, perennial and allotetraploid [2n = 28]). All the other species, which either do not cross with cultivated species or, when they do cross, the hybrid's fertility has to be restored through special techniques (Hanna 1987), are included in the tertiary gene pool. Four different races of pearl millet have been recognised (Brunken et al. 1977): (i) typhoides (ii) nigritarum (iii) globosum (iv) leonis.

Adaptation

The two major advantages that facilitated the domestication and cultivation of pearl millet as a wild cereal were: (i) aggressive colonizing ability of disturbed habitats, and (ii) pre-adaptation to difficult crop production regions (de Wet et al. 1992). The ability of wild progenitors of pearl millet to withstand heat and drought stress (common in Africa) was responsible for the success of pearl millet as a major cereal crop of arid and semi-arid regions. Further, as wild pearl millet was a typical grass, it had features reminiscent of grasses, such as production of a large number of caryopses that tolerate a harsh desert climate. Another important feature was dormancy which provided the ability to tide over unfavourable climatic conditions and also to germinate under favourable climatic conditions. Profuse tillering coupled with the ability to produce new tillers under favourable conditions aided in development and reproduction. Most of these features/adaptations were retained in cultivated pearl millet.

Pearl millet employs two different strategies of opportunism (for moisture availability) and tolerance (for heat stress) to counter the two major abiotic stresses. Additionally, under high temperature conditions pearl millet has the capacity for rapid growth and development. The climatic conditions in most of the arid and semi-arid regions of Africa and Asia allow for only a short growing period. To survive and be able to be relatively productive under such conditions requires the development of certain traits (such as rapid growth/development and heat/drought tolerance) which are observed in pearl millet. Other characters which contribute to the success of a cereal under harsh climatic conditions include seed germination, seed survival, seed viability, rapid growth and development and relatively good seed set under moisture and heat stress conditions. Most of these characteristics are observed in pearl millet making it a crop of choice in these regions.

Pearl millet has been cultivated for centuries in difficult crop production environments and man-disturbed habitats around the world owing to its resilient nature and ability to withstand harsh climatic conditions (explained above). In addition to low water requirement, pearl millet is particularly adapted to drought prone regions, regions with poor soil fertility and hot/dry climates as in the case of sub-Saharan Africa and parts of Asia. A deep root system coupled with a short life cycle enables pearl millet to be grown in areas with low rainfall, ranging from 200 to 600 mm (Panaud 2006), unfavourable for other cereals such as maize or sorghum. Short duration pearl millet cultivars (65–75 days to mature) could be cultivated as "catch crops" in areas where the main crop of the season fails or as a contingency plan under crop failure situations, ensuring the farmer of at least minimum produce/returns. Pearl millet is a low maintenance crop owing to its natural ability to tolerate different biotic and abiotic stresses (FAO and ICRISAT 1996). In addition to its adaptability and nutritional composition, another advantage with pearl millet (other millets also) is that its seed does not require any special storage facilities as it stores well with minimum precautions at appropriate moisture content [~12–13 %]. This provides the much required food security to farmers with uncertain/unstable income or access to other staple foods.

Reproductive biology

Pearl millet is a highly cross-pollinated crop with more than 85 % out-crossing. Its floral biology is unique among the major crop species as its hermaphrodite flowers are protogynous (stigma emerging before anther emergence) with the fully emerged and unpollinated stigmas normally remaining receptive for 3–4 days. Pearl millet inflorescence is a false spike, with the panicle size ranging generally from 20 to 40 cm in length (with some germplasm accessions up to 1.5 m long) and 3 to 5 cm in diameter. The panicle is terminal, varying in shape from cylindrical to candle-shaped. The spike consists of a central rachis which is closely packed with fascicles. Each fascicle consists of one or more spikelets. An inflorescence contains, on average, 1600 spikelets (Khairwal et al. 1990). The spikelets are small, lanceolate, and acute. Each spikelet consists of two glumes (outer and inner) and between the glumes, there are two florets. The lower floret is staminate and the upper floret is hermaphrodite. Spikelets are generally bifloret (Maiti and Bisen 1979). The staminate flower has one lemma and one palea, and enclosed between them is the androecium with three stamens. The upper hermaphrodite floret has a broad, pointed lemma and a thin, oval palea, and the androecium and gynoecium are enclosed between them. The pearl millet androecium consists of three hairy anthers (yellow or purple), each attached to a long filament. The gynoecium consists of an ovary with two styles and a feathery stigma. The pistil in its young stage shows two carpels, one larger than the other.

Flowering starts after the emergence of the panicle from the boot, but in some genotypes style exertion commences before completion of panicle emergence. Stylar exertion begins first in the florets in the central upper portion of the panicle and then progresses upward as well as downward. The stigma remains receptive for 18–24 h after full emergence. Anther emergence begins one day after the emergence of the stigma is complete on the panicle. It first starts in the hermaphrodite florets followed by the staminate florets. Anther emergence starts in the upper portion (at about the two-thirds point) of the panicle and proceeds in both directions. The first flush of anthesis is completed in ~7–12 days and the process may continue for up to three weeks. Seed-set can be seen in the panicle about a week after fertilization.

Production constraints

The major pearl millet production areas are in the arid regions of Asia and Africa where the rainfall is low and its distribution erratic (Murthy et al. 2007). In many of the pearl millet production areas significant amounts of water are lost either as surface runoff or as deep drainage which could be harvested for providing supplemental irrigation (Murthy et al. 2007). In addition to water harvesting, in-situ water conservation methods need to be developed and adopted. Integrated nutrient management practices that are affordable even by the poorest farmers are essential and can significantly enhance water use efficiency and crop productivity.

Drought can occur at any growth stage, but terminal (post-flowering) or end-of-the season drought is more important and better understood than pre-flowering stress (Rai et al. 1999). Mahalakshmi and Bidinger (1985) have shown that post-flowering crop growth is most sensitive to moisture deficits and Fussell et al. (1991) found that grain yield was reduced by ~40–49 % under terminal drought conditions. High temperature stress is another important production constraint in pearl millet. Increase in air and soil temperatures results in yield reduction owing to a variety of reasons. Although the thermo-tolerance levels of pearl millet are relatively better than other cultivated cereals, crop stand failure due to heat stress is observed in arid regions (de Wet et al. 1992). Most pearl millet cultivation is on marginal soils that have low inherent fertility. As most of the producers of pearl millet are smallholder or marginal farmers, application of nutrients or other agricultural inputs is also low, resulting in poor yields.

Downy mildew (DM) caused by *Sclerospora graminicola* (Sacc.) Schroet is a major biotic constraint in pearl millet production causing severe crop and economic losses. DM damage of epidemic proportions has occurred in high-yielding single-cross hybrids in India and Africa (Murthy et al. 2007). Another emerging disease causing significant yield grain and forage losses in pearl millet is leaf blast or leaf spot, caused by *Pyricularia grisea* (Cooke) Sacc.; (teleomorph; *Magnaporthe grisea* (Herbert) Barr; Sharma et al. 2013). Other diseases affecting pearl millet include smut (*Tolyposporium penicillariae* Bref.), ergot (*Claviceps fusiformis*, Loveless) and rust (*Puccinia fusiformis* var. *indica*) (Ramachar & Cumm,). In sub-Saharan WCA, witchweed (*Striga hermonthica*), a destructive parasitic weed, is a serious threat to pearl millet production (Wilson et al. 2004). Under drought conditions, *Striga* infestation can cause up to 100 % grain yield losses (Kountche et al. 2013).

Insects are not a major concern for pearl millet production in India, but some of them are important under sub-Saharan African conditions. Though the reported number of pests exceeds 100 in pearl millet, only a few of them cause significant economic losses. The major pests of pearl millet include shoot fly (*Atherigona approximata* Malloch), stem borer (*Chilo partellus* Swinhoe), ear head caterpillars (*Helicoverpa armigera* Hubner), white grub (*Holotrichia longipennis*) and grey weevil (*Myllocerus maculosus* Desb.; Yadav et al. 2012). Introduction of uniform and high-yielding cultivars has led to an increase in pest problems across the world. The losses due to insect pests and their distribution vary from region to region. Agronomic, chemical and biological control methods have been recommended as part of integrated pest management for control of major pests.

Breeding for adaptation to climate change and improved food/nutritional security

Pearl millet is mostly cultivated under low-input and rainfed conditions in Asia and Africa. It is affected by a diverse range of abiotic and biotic constraints, but it is the best, if not the only, option of providing food and nutritional security to the rural poor of the arid tropics in Sub-Saharan Africa and NW India. The constraints occurring in a particular region are continuously altering both spatially and temporally due to changing climate. Therefore, to be able to yield well under such conditions, cultivars (varieties/hybrids) must tolerate biotic and abiotic stress conditions. Further, low yield potential of landraces and even most of the improved varieties remains the major biological constraints to productivity improvement, especially in Africa and North-western India. There is a need to improve yield potential of pearl millet in the arid zone of India as well as in sub-Saharan Africa, which have not yet benefitted from pearl millet hybrid technology. This obviously requires strategic planning of crop improvement programs.

Cultivar options

Both open pollinated varieties (OPVs) and hybrids can be produced in pearl millet owing to its highly cross pollinating nature and availability of commercially exploitable cytoplasmic male sterility (CMS) systems. Despite being low yielding compared to hybrids, OPVs have considerable variability which aids their stable performance under resource constrained and harsh environments, where pearl millet is usually an important crop. Additionally, OPV seeds can be re-used by the farmers over a period of 2 to 3 years. In Asia (India, in particular) mostly OPVs were cultivated until the mid-1960s; their cultivation took a backseat with the advent of better performing hybrids. Later, during the 1970s, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) initiated an OPV development breeding program. As a result of concerted efforts at ICRISAT and partners, WC-C75, the first ICRISAT-bred OPV was released for cultivation in 1982. Though the program itself was a success, it was realised that the best hybrids out-yielded the OPVs by ~30 % (Table 1). The interest and involvement of private sector seed industry and farmer preference for uniform cultivars gave an impetus to the development of a wide range of hybrids (Fig. 3). Though top-cross hybrids (TCH) and three-way hybrids were developed and tested on a large scale, they had no specific advantages over single-cross hybrids. Research at ICRISAT has shown that a high-yielding topcross hybrid (ICMH 312) was comparable to a single-cross hybrid (ICMH 451) in terms of grain yield and maturity (Rai et al. 2006). TCHs and inter-population hybrids had an overall yield advantage of 14–52 % and 27–59 %, respectively, over the best OPV in trials conducted in sub-Saharan Africa.

Germplasm utilization

Availability of a diverse range of germplasm for different traits is very crucial for crop improvement. Apart from other

Fig. 3 Cultivation of hybrid pearl millet. *Source*: Dr. R.S. Mahala, Pioneer Seeds Pvt. Ltd

genebanks, ICRISAT has a large collection of global pearl millet accessions. ICRISAT has also developed several composites and OPVs which have been widely used by public institutions and private sector breeding programs. Additionally, the composites and OPVs were utilized in developing several elite lines and hybrid parents by ICRISAT. ICRISAT-bred pearl millet breeding lines have also been found to be good sources of non-target traits such as grain quality (enhanced iron and zinc content) and stress resistance factors (such as blast and rust resistance and heat tolerance) for which no specific selection had been made.

Utilization of germplasm in crossing programs with either maintainer lines (B-lines) or restorer lines (R-lines) is an important issue. Experimental evidence indicates that iniadi x non-iniadi crosses are highly heterotic. Generally, the iniadi germplasm is crossed with B-lines for seed parent development and non-iniadi germplasm with R-lines for R-line development (K. N. Rai, personal communication). Elite breeding lines so developed are distributed to both the public and private sector breeding programs to be used in B-line and R-line crosses. This has helped to maintain significant diversity among B- and R-lines. Molecular marker analysis (of the 98 B-lines and 115 R-lines developed at ICRISAT) has shown distinct clustering of B-lines and R-lines with few exceptions (Nepolean et al. 2012). Further, the study also identified diversity within the B-lines and R-lines suggesting further genetic gain can be made from B x B and R x R crosses. Development of heterotic pools (based on diversity) coupled with millet genome sequencing (nearing completion) can enhance the exploitation of heterosis in an efficient way.

Table 1 Grain and dry fodder yield of pearl millet OPVs and hybrids in AICPMIP trials

Year	Mean grain yield (kg ha^{-1})		Mean dry fodder yield (t ha^{-1})	
	Hybrids[a]	Best hybrid[b]	Hybrids[a]	Best hybrid[b]
1996	1775 (24)	2213 (31)	3.1 (−6)	3.5 (−5)
1997	1676 (10)	2047 (26)	3.4 (3)	4.0 (8)
2000	1117 (26)	1449 (40)	2.0 (5)	2.1 (5)
2001	1971 (27)	2191 (30)	2.9 (−17)	3.6 (3)
Mean	1621 (22)	1975 (32)	2.9 (−4)	3.3 (3)

Adapted from Gowda et al. 2006

[a] Figures in parentheses indicate superiority (%) over OPVs

[b] Figures in parentheses indicate superiority (%) over best OPV

Target traits

The improvement in performance of different traits has been possible due to genetic improvement of the components involved. In the case of grain yield, these components include productive tillers, panicle size, panicle compactness, grain number/panicle and grain size. Therefore, breeding programs have focused on developing hybrids with large panicle size, high grain number and larger grain size. In addition to yield, biotic and abiotic constraints (introduced in the preceding paragraphs) are important determinants of a cultivar's yield potential. Besides grain yield, improvement in stover yield is also required. Incremental increases in stover yield is mostly due to longer crop duration and taller cultivars. Blümmel and Rai (2003) have reported an inverse relationship of stover crude protein content, grain yield and stover yield. Interestingly, no relationship was found between stover and grain yield implying that increment in grain yield will not affect stover yield and vice versa. As grain yield and stover quality are traits that are not related, it is possible to achieve better stover quality without affecting grain yield (Blümmel et al. 2007). In addition to grain and stover yield, qualitative traits such as disease (downy mildew/rust/blast) resistance, stay green and digestibility are also important. At ICRISAT some experimental hybrids of pearl millet [16.1–18.6 t/ha dry forage yield] out-yielded commercial sorghum-Sudan grass hybrids by 22–41 %. Development of specific A-lines coupled with selection for specific combining ability in the OPV pollinators may aid in developing high forage yielding hybrids.

Significant progress has been achieved with respect to the important biotic stress, downy mildew (DM), including the understanding of inheritance of resistance, development of effective screening techniques (both field and greenhouse), and availability of diverse sources of resistance to different pathotypes. These efforts have prevented the occurrence of major DM epidemics, especially in India. DM resistance is multigenic and controlled by several quantitative trait loci (QTL) including both major and minor ones. Many of the QTL identified confer only partial resistance and rarely does any single QTL have a large effect. HHB 67, a popular pearl millet hybrid in India was improved for DM resistance using both marker-assisted backcrossing and conventional backcrossing. Two major QTL were transferred from ICMP 451 (donor) to H77/833–2 (male parent) by adopting marker-assisted backcrossing (Breese et al. 2002). Interestingly, conventional backcrossing was adopted to transfer the DM resistance from ICML 22 (donor) to 843 A/B (female parent). The new 'HHB 67 Improved' has significantly greater resistance to DM and gives 5–10 % higher yields of both grain and stover than the original hybrid HHB 67.

Leaf blast is another emerging problem in pearl millet. Effective screening techniques along with different sources of resistance have been identified. Early flowering and blast tolerant accessions having high scores [≥7] for grain and fodder yield have been identified at ICRISAT (Sharma et al. 2013). But, additional efforts are required to achieve success on a par with that of DM control. The severity of rust incidence has increased in recent times. A simple and effective field screening technique for rust has been developed for peninsular India. Despite identifying rust resistance sources and developing greenhouse screening techniques (at ICRISAT), a targeted breeding program for rust resistance is yet to be initiated.

Terminal drought is a serious abiotic constraint affecting pearl millet production. The unpredictable nature of drought occurrence (duration, intensity and frequency) coupled with lack of effective field screening techniques, non-availability of tolerant sources and complex genetics influencing this trait are major hindrances to breeding drought tolerant pearl millet. Characterization of the drought tolerance trait in pearl millet has been reported by several authors. QTL responsible for yield under terminal drought conditions have been identified (Yadav et al. 2002) and confirmed (Yadav et al. 2004). Further, the role of the drought tolerance QTL in achieving higher grain yield under stress conditions has been established (Serraj et al. 2005). Interestingly, near-isogenic lines (NILs) containing a major drought tolerance QTL have shown variation in root growth under drought conditions (Vadez et al. 2007). Drought tolerant genotypes or those containing the drought tolerance QTL had less water loss per unit leaf (Kholová et al. 2010a). Further, it was shown that this QTL was also related to high ABA levels and sensitivity of transpiration to high vapour pressure deficit under well-watered conditions (Kholová et al. 2010b). Therefore, it is hypothesized that these traits would help in conserving water under non-limiting conditions and increase its availability during grain filling, which is crucial under terminal drought conditions.

Availability of assured irrigation during the summer (February-May) has led to cultivation of pearl millet during this season, mostly in north and north-western India, including Gujarat, Rajasthan and parts of Uttar Pradesh. The air temperatures during the flowering period in summer are usually >42 °C and may reach 46-48 °C, leading to poor seed set and lower grain yields but a few hybrids with good seed set and high yields of grain [4–5 t/ha] and fodder [8–10 t/ha] yield are being cultivated. Breeding programs for heat tolerance have been started at ICRISAT and also by some private seed companies. Identification of sources of heat tolerance is also being carried out at the 'ICAR-Central Arid Zone Research Institute, Jodhpur, India'.

Iron (Fe) and zinc (Zn) deficiencies have been recognised as serious health problems world-wide. ICRISAT with funding support from the 'HarvestPlus Challenge Program (CGIAR)' has developed cost-effective and reliable screening techniques to determine the content of both the nutrients in the grain. Additionally, large variability for Fe and Zn has been observed among breeding lines and advanced progenies (Table 2). Some of the lines were found to contain >100 ppm Fe density and >60 ppm Zn density (Table 2) 'Dhanashakthi', a high Fe [71 ppm] pearl millet variety has been developed by ICRISAT in collaboration with several NARS partners (Rai et al. 2014). Gradually,

Table 2 Variability of grain Fe and Zn content in pearl millet*

Material	No. of Entries	Number of entries in micronutrient (ppm) class					
		<40	41–60	61–80	81–100	101–120	>121
Iron (Fe)							
Advanced breeding lines	386	97 (25)	181 (47)	89 (23)	19 (5)	0	0
Population progenies	232	0	5 (2)	65 (28)	116 (50)	39 (17)	7 (3)
Zinc (Zn)							
Advanced breeding lines	386	185 (48)	189 (49)	12 (3)	0	0	0
Population progenies	232	0	116 (50)	107 (46)	9 (4)	0	0

Note – figures in parentheses indicate % of entries in each class

* Adapted from Rai et al. 2012

breeding for high Fe and Zn is being taken up at different NARS partners and private seed companies along with ICRISAT.

Biotechnology is an emerging resource for pearl millet improvement. The benefits of these resources have been limited in pearl millet compared to other cereal crops such as rice, wheat, maize or barley (genomes also sequenced). Recombinant DNA technology could very well complement conventional breeding efforts by assisting the plant breeders in making crop improvement relatively faster and more efficient. Marker-aided selection/breeding of different traits with the main objective of assembling as many resistance/tolerant characters as are essential for realizing high crop yields under stress conditions could prove to be very cost-effective. Pearl millet hybrid 'HHB-67 (Improved)' developed by collaboration between Haryana Agricultural University, Hisar, India and ICRISAT, is the first product of marker-assisted breeding in pearl millet. The problem of 'intractable' or difficult to breed traits could be addressed through crop genetic engineering, whereby crucial tolerant traits can be directly transferred into well adapted local varieties.

'Agro-ecological focus'

Local consumption needs and preferences add another dimension in developing improved pearl millet varieties that meet the needs of the local farmers. Therefore, a successful pearl millet breeding program for these challenging environments must consider the consumer needs and varietal preferences of the farmers. New cultivars with required resistance/tolerance to different stresses could be developed by selecting appropriate parent material followed by evaluation and selection under local conditions. If possible, the selections should be carried out using farmer participatory approaches. The urgent necessity is for a 'local agro-ecology-based' crop improvement program that can aid in pyramiding a set of traits/genes that reduces yield losses and confers yield stability. To achieve these targets an efficient coordination between different national agricultural research systems (NARSs) and international agricultural research centres (IARCs) should be ensured. IARCs should take the lead in tackling certain 'intractable' constraints in pearl millet production such as drought screening or downy mildew/*Striga* resistance. IARCs may have certain advantages in terms of better resources, equipment, or technological know-how that could be effectively utilized in overcoming at least some of these difficult problems.

Breeding efforts (both conventional and molecular) directed towards enhancing nutritional content of pearl millet should be a priority. But the nutritional improvement programs should take into account local preferences and choices before developing improved cultivars. As already discussed in the preceding paragraphs, evaluation of parental lines, selection, screening/evaluation and development of cultivars should be targeted to the local agro-ecologies as a primary objective. These initiatives if taken up in a systematic manner could provide the dryland farmers of Asia and Africa the much deserved food, economic, nutritional and health security.

Pearl millet production in Africa and India

Mono-cropping of pearl millet is practised in West Africa, in addition to being cultivated as an intercrop with legumes such as cowpea (*Vigna unguiculata* (L.) Walp), groundnut (*Arachis hypogaea* L.), grain sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays*) (Andrews 1974). Growing pearl millet as a dominant component of an intercropping or a mixed cropping system is a traditional crop cultivation practice, especially in the marginal environments where the crop is managed with negligible external environments and farm produce is mostly consumed by farming households and little, if any, surplus enters the local markets. Intercropping is a rational strategy for profit maximization and risk minimization accruing from higher and stable total yield, and more efficient use of human, biological and natural resources. In WCA, more than 85 % of pearl millet area has been reported to be intercropped or grown as a mixed crop (Fussell et al. 1987). The most common intercrop components in pearl millet-based cropping systems are legumes, which are also used as rotational crops. Legumes provide nutritious food and feed, increase soil fertility through biological nitrogen fixation, reduce disease/insect pest incidence, add organic matter and help conserve farming resources, and provide for more flexible weed control (van Duivenbooden et al. 2000).

Intercropping studies involving millet-cowpea and millet-sorghum-cowpea indicated that water use efficiency of pearl millet improved for grain production (Oluwasemire et al. 2002). Crop rotation of pearl millet with potato was reported to be an effective way to control root lesion nematode thereby providing an environmental friendly alternative to chemical application (Sritharan et al. 2007). Additionally, it has been observed that resistant pearl millet hybrids, when rotated with groundnut, are effective in controlling the population of *Meloidogyne arenaria* (peanut root-knot nematode) and increase groundnut yields (Timper et al. 2007). Pearl millet is widely intercropped with or grown in rotation with cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogaea*) in African regions. Pearl millet is also grown in rotation, and sometimes intercropped with sorghum (*Sorghum bicolor*) and maize (*Zea mays*), even if it is known that rotation of cereals with cereals leads to depletion of the natural resource base. In parts of western Africa, especially those with bimodal rainfall distribution, a unique cropping system exists where early-maturing pearl millet is grown with late-maturing photosensitive pearl millet in mixed stands.

In India pearl millet is often cultivated in rotation with groundnut, cotton (*Gossypium herbaceum*), castor (*Ricinus communis*), sorghum and other millets such as foxtail or finger millet. A three year rotation (pearl millet-cotton-sorghum or pearl millet-sorghum-cotton) is followed in cotton and sorghum producing areas (Khairwal et al. 2007). Monocropping of pearl millet in successive years is practised on sandy soils. A 3-year rotation system is followed in parts of Southern India which includes pearl millet-finger millet-groundnut-rice-sugarcane. In arid regions of India, cluster bean (*Cyamopsis tetragonoloba*)-pearl millet rotation has increased the productivity of pearl millet where previously fallow-pearl millet or pearl millet-pearl millet was practised. In the dry regions of North-Western India, pearl millet is rotated with moth bean (*Vigna aconitifolia*) or mung bean or green gram (*Vigna radiata*). Alternatively, pearl millet is followed by fallow or mustard (*Brassica juncea*), and cluster bean. Intercropping of pearl millet is practised in different regions of India. Pearl millet is mostly intercropped with cluster bean, cowpea, green gram (Fig. 4), sesame (*Sesamum indicum*) and moth bean (Fig. 4) in Northern or North-Western India. In Central and Southern India, pearl millet is mostly intercropped with pigeonpea (*Cajanus cajan*), soybean (*Glycine max*), sunflower (*Helianthus annuus*), and groundnut (Khairwal et al. 2007). Mixed cropping of pearl millet with pigeonpea, cluster bean, cowpea, green/black gram, sorghum or vegetables is followed in some parts of India and is usually adopted to meet the domestic needs of individual farmers.

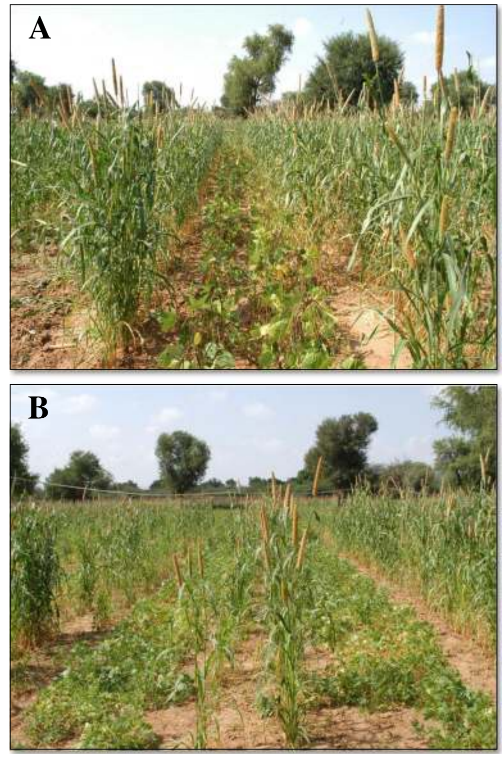


Fig. 4 Pearl millet intercropping systems (**a**) with green gram (*Vigna radiata*), and (**b**) with moth/dew bean (*Vigna aconitifolia*) as practiced in Rajasthan, India

Pearl millet is a hardy crop that withstands deficiencies in soil moisture and nutrient availability relatively better than other crops under similar conditions. It is cultivated on sandy oxisols (low available nitrogen (N) and phosphorus (P) in WCA and sandy loams or loamy soils in other parts of sub-Saharan Africa (Krishna 2014). Sandy soils possess low water retention capacity allowing easy percolation of rainwater down the soil profile. In Eastern Africa, pearl millet is cultivated on alfisols and lixisols. In the USA, it is grown on low productivity soils such as ultisols and mollisols. Pearl millet is cultivated on sandy soils in North-Western India but it is also grown on a wide variety of soils in other parts of India including red sandy/loamy soils, alluvial soils and also on mixed red and black soils. It is grown on medium black soils, sandy and gravelly soils that are poor in fertility and low in organic matter content (Khairwal et al. 2007). Well-drained sandy loamy soils to loamy soils without salinity/alkalinity are best suited for pearl millet cultivation. However, pearl millet tolerates acidic and saline soils much better than many other major cereals but does not perform well on soils prone to waterlogging (Khairwal et al. 2007). Tillage practices may improve crop growth and yield by improving soil porosity leading to higher root density, rooting depth, better moisture storage and harvesting, reduced evaporation and better water use efficiency (Nicou and Charreau 1985) but adoption of tillage practices by farmers of WCA has been limited owing to lack of resources.

Pearl millet growing regions of WCA experience arid or semi-arid climates with a short rainy season lasting from June to September (Krishna 2014). The region is prone to recurrent droughts which are a major constraint for crop production. Being a tropical zone, this region receives sufficient heat [2400 to 2600 degree days] for pearl millet cultivation. Under favourable conditions profuse tillering is observed with rapid biomass production during 60–70 days from the seedling stage. Several soil nutrient studies in WCA have indicated that nutrient removal is far greater than addition. Based on a study conducted in southern Mali, pearl millet absorbs soil nutrients intensively if available, leading to high nutrient concentration in the harvested product (Smalling et al. 1993). Low inherent soil nutrient status, high soil nutrient depletion and low soil nutrient application are important factors in decreasing crop productivity in Africa. Phosphorus followed by nitrogen are reported to be the most limiting nutrients for pearl millet in West Africa (Bationo and Mokwunye 1991). Therefore, pearl millet responds very well to fertilizer application. Soil organic matter (SOM) content of sandy soils is low. Application of farm yard manure (FYM) along with inorganic fertilizers produces significant increases in grain and forage yields. Application of mulch is advocated in areas with wind erosion (as in the Sahelian zone). Stone rows increased yield by 35–65 % in Burkina Faso (Ouattara et al. 1999). Stroosnijder and Hoogmoed (2004) reported that stone rows and vegetative barriers reduced runoff by 20 %, thereby increasing soil moisture and reduced carbon loss due to erosion. These practices help to prevent loss of top soil and fertility, maintain crop growth and enhance grain yield. In regions with high wind erosion, wind breaks consisting of different tree species such as *Acacia*, *Bauhinia*, and *Ziziphus* are useful.

Pearl millet growing on the Indian subcontinent is similar to that of sub-Saharan African regions with regard to climatic conditions. Pearl millet is mostly cultivated as a rainfed crop between June/July and September/October. To a limited extent, it is also cultivated as an irrigated summer crop (January to May) in India (Khairwal et al. 2007). The average rainy season temperatures range between 24 and 32 °C; pearl millet can tolerate temperatures up to 38-40 °C (Krishna 2014). Some hybrids have good seed set even at air temperatures of 46 °C and are cultivated in parts of India during the summer if irrigation is assured (Khairwal et al. 2007). North-Western India is the major pearl millet cultivating region in India wherein the average annual rainfall is about 200 to >400 mm, and up to 900 mm; Krishna et al. 2014). Though pearl millet is mostly cultivated as a rainfed crop, moisture availability at tillering, flowering and seed setting is critical for high yields.

In India, pearl millet's response to nitrogen supplementation (usually the most deficient nutrient) is highest. Significant increases in grain and stover yield in response to application of small amounts of N and P at the time of sowing or three to four weeks after sowing as top dressing (microdose) have been demonstrated in field studies in Africa (Table 3). The response and dosage of nitrogen depends upon several factors, including soil type, nutrient status of the soil, climatic conditions, cultivar type, water holding capacity of the soil and moisture availability. Pearl millet also responds to phosphorus, but yield responses to potassium application have not been observed. Further, application of zinc increases both grain and stover yield coupled with increase in grain protein content (Jakhar et al. 2006). Application of FYM along with fertilizers improved the crop stand, increased yield, and reduced soil crusting (Jakhar et al. 2006). Application of bio-fertilizers such as *Azospirillum brasiliense* along with low levels of nitrogen [10–40 kg ha^{-1}] increased grain yields by 21–83 % (Gautam 1990; Table 3).

Area, production and yield trends

India is the largest pearl millet producing country in Asia and the world, both in terms of area and production. During 2010–2012 the average pearl millet area in India was 8.5 million ha and the average production 9.4 million tons. Western and Central Africa (WCA) is the largest pearl millet producing region in Africa and the world (Figs. 1 and 2). Segregated data on the pearl millet area for WCA is not available, but pearl millet is assumed to account for 95 % of the total area in WCA. During 2010–2012, the average pearl millet area was 15.3 million ha and the average production was 10.3 million tons in WCA. In the Southern, Eastern and North Africa (SENA) region there is also no segregated data for pearl millet. Sudan has the largest millet area of 2.18 m ha, of which more than 95 % is assumed to be pearl millet. Overall, the SENA region has ~3.0 m ha under pearl millet cultivation.

The second half of 1980s was a landmark in the enhancement of pearl millet productivity in India. The average grain yield was 465 kg/ha during 1986–1988 but during 2010–2012 it was 1110 kg/ha, an increase of 138 %, and average rate of yield gain of over 5 %/year (Fig. 5). This led to an 89 % increase in production even though the cropped area declined by 19 %. This remarkable increase in pearl millet productivity was largely due to the adoption of high-yielding cultivars (mostly hybrids) and to some extent due to improved crop management technologies. Large-scale adoption of high-yielding cultivars (of the >60 % pearl millet area under hybrids and improved varieties, more than 90 % is under hybrids) by Indian farmers is due to multiple factors including: (i) availability of hybrids for different agro-climatic zones with a wide range of maturity period [60–90 days] (ii) seed cost recovery with even minimal [~10 %] yield advantage over varieties; and (iii) presence of an efficient hybrid seed

Table 3 Yield response of pearl millet to fertilizer application

Treatments	Grain yield (kg ha^{-1})	% Increase of grain yield over control	Stover yield (kg ha^{-1})	% Increase of stover yield over control
Fertilizers*				
Zero	447	-	1347	-
Microdose	721	61	2228	65
Microdose + 20 kg P ha^{-1}	849	90	2657	97
Microdose + 40 kg P ha^{-1}	906	103	2683	99
Microdose + 30 kg N ha^{-1}	739	65	2449	82
Microdose + 60 kg N ha^{-1}	777	74	2586	92
Microdose + 20 kg P ha^{-1} + 30 kg N ha^{-1}	973	118	2832	110
Microdose + 20 kg P ha^{-1}+ 30 kg N ha^{-1}	1043	133	3259	142
Bio-fertilizers§				
Control	1145	-	-	-
Azospirillum	1382	21	-	-
10 kg N ha^{-1} + Azospirillum	1559	34	-	-
20 kg N ha^{-1} + Azospirillum	1835	60	-	-
40 kg N ha^{-1} + Azospirillum	2097	83	-	-

Note: 'Microdose' involves applying a small and affordable amount of fertilizer with the seed at sowing or as top dressing 3–4 weeks after emergence

- Bagayoko et al. 2011; § - Gautam 1990;

production, distribution and marketing system (Yadav et al. 2012). The adoption of high-yielding hybrids varies considerably across India, with Gujarat and Haryana having the highest rates of adoption, while Rajasthan has the lowest.

A comparison of productivity gain from 1989 to 1993 (taken as the base) to 2009–2013 showed that pearl millet registered a productivity gain of ~42 %, which was much higher than those reported for rice and wheat (Table 4). It is often argued that since pearl millet productivity level is much lower than for rice and wheat, such comparisons in terms of per cent productivity grain are not realistic. Annual rate of pearl millet productivity was assessed from 1960 to 2010, by dividing it into two periods of 25 years each (1960–1985 and 1986–2010; Yadav et al. 2012). The average grain yield during 1960–1962 was 350 kg/ha and

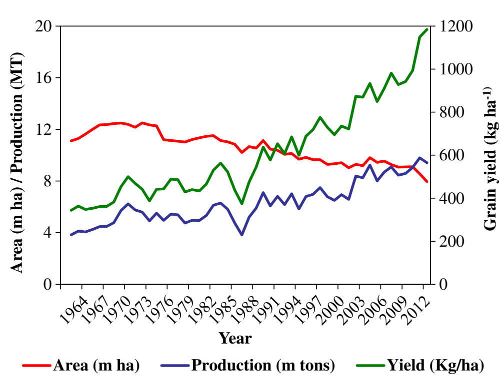


Fig. 5 Three-year moving average for pearl millet area, production and grain yield for India. *Source*: Directorate of Economics and Statistics, India (http://eands.dacnet.nic.in/APY_96_To_06.htm)

productivity increased ~6.3 kg/ha/yr. During the second period, the average productivity in 1986–1988 was 465 kg/ha, but annual productivity increased by ~20 kg/ha/yr. The higher rate of increase observed during this second period was due to several reasons as explained above in addition to the greater number of cultivars released in 1986–2010 [107] than in 1960–1985 [43]. Further, lack of occurrence of major disease epidemics of downy mildew, increased involvement of the private sector in pearl millet seed production, distribution and marketing coupled with investment in research and development of pearl millet led to an overall increase in productivity. Much of this yield gain has occurred due to hybrid adoption in relatively better endowed and high yielding environments, which receive more than 400 mm of rainfall. There has been apprehension about the productivity gains that can be achieved through hybrid adoption in low productivity environments, which are typical of arid environments. While the magnitude of heterosis is higher in higher yielding environments, a significant and economically exploitable level of heterosis has also been observed in low yielding environments (Rai et al. 2006).

Case Study 1: Adoption of pearl millet (ICTP 8203) by farmers of Rajasthan and Uttar Pradesh in India (Mula et al. 2010)

ICTP 8203 is an open pollinated variety (OPV) developed at ICRISAT, Patancheru, India. Despite stiff competition from hybrids, it is cultivated due to its excellent adaptability to low fertility soils, early maturity, drought tolerance, large grain size and preferred grain traits such as dark gray color. Though it was released for Andhra Pradesh and Maharashtra states, it was adopted in Rajasthan and Uttar Pradesh through a chain of input dealers, government camps and information from co-farmers. The tangible benefits of adopting ICTP 8203 were the fulfilment of food and fodder requirements of the farmers. However, a major constraint, according to dealer-respondents, was insufficient seed availability leading to spurious seed and black marketing. ICTP 8203 has become the mainstay of the pearl millet cropping system of farmers in the drier regions of Uttar Pradesh and Rajasthan, where it is popularly called 'Bhim' (a mythological character with strong physique) or 'Sher' (meaning lion). It shows good response to favourable growing conditions, and is not affected by major pests or diseases; these traits greatly contribute to its popularity among the farmers.

Additionally, the 'roti' (unleavened bread) prepared from the grain is more palatable, and provides more energy than other varieties. ICTP 8203 has high levels of iron (>65 ppm) and zinc (>45 ppm) and has been recommended for people suffering from diabetes. Most of the farmers growing this variety consider livestock and '*bhim bajra*/*pearl millet*' as wealth. Based on farmer's personal experience, the fodder and grain quality along with yield of ICTP 8203 have not been surpassed by any other variety/hybrid grown under similar conditions. The farmers' major concern was with the deteriorating quality of seed available from seed dealers. Farmers of this region do not adopt hybrid seeds due to the higher risk of failure of materials about which they do not have much knowledge. Familiarity with the crop and variety is a major reason for the adoption of ICTP 8203 by farmers of Uttar Pradesh and Rajasthan. Though the area under ICTP 8203 cultivation has shrunk during recent years, breeders from the industry are hopeful that it will be in demand for at least another decade owing to its potential to withstand climate change and erratic rainfall.

The average landholding and area under pearl millet cultivation of farmers involved in the case study was ~6.0 and 0.9 ha respectively. Based on the information provided by the farmers, large variation was observed for grain yield (1040 to 4800 kg/ha) and stover yield (2500–13,400 kg/ha) probably owing to differences in the agronomic practices adopted. The average seed rate was 5.25 kg/ha, slightly higher than the recommended rate of 4 kg/ha. Farmers who used the optimum seed rate (4-5 kg/ha) had the highest grain (3200–4800 kg/ha) and stover yields (10,000–13,400 kg/ha). These farmers invested much more (compared to others) in crop management and post harvesting operations, demonstrating that some farmers had the required knowledge and were also willing to adopt new technologies. The average gross income from grain, stover and net income was Rs. 15,569, Rs. 7560, and Rs. 17,000 (1$ = ~Rs.46) per hectare respectively.

In WCA, pearl millet production during 2010–2012 increased by 31 % (from a base level of 7.9 million tons during 1986–1988), but almost all of this was due to increase in area, which increased by 45 % (from a base level of 10.6 million ha during 1986–1988; Fig. 6) as the productivity increase of 8 % was negligible. The central reason for this has been the unavailability of high yielding cultivars (mostly hybrids) and unavailability of seed of improved OPVs, not to mention the negligible adoption of improved crop management technologies. In this context, the Indian success story has lessons regarding what can be achieved in WCA and other countries with similar agro-ecological conditions.

Case Study 2: Adoption and impacts of pearl millet varieties in Nigeria (Ndjeunga et al. 2011)

A study was conducted in 119 villages (994 households) in six states (Borno, Jigawa, Kano, Katsina, Yobe, and Zamfara) of northern Nigeria that cultivate pearl millet. The primary objective of the study was to evaluate the adoption and impact of four modern pearl millet varieties (SOSAT C88, LCIC 9702, GB 8735 and ZATIB). Average landholding size of farmers in this region was ~3.3 ha, of which ~1.0 ha was under pearl millet cultivation. Among the farmers, only ~45 % of them had some knowledge regarding the modern pearl millet varieties and this also differed among the states studied. About 38 % of the pearl millet farmers had actually adopted the modern varieties i.e. ~84 % of farmers who had prior knowledge about modern varieties. Further, except for Yobe and Jigawa, the other four states had adoption rates of >43 %. Among the modern varieties, SOSAT C88 was the most popular, occupying the largest planted area among modern varieties. Households with better or more physical, social and human capital were better at adopting modern varieties. The farmers' preferred and non-preferred traits of different varieties studied include (i) SOSAT C88 – medium maturity (90 days), tolerance to pests, bold grain, grain color, and ease of processing (preferred); smaller head, low fodder yield, and short shelf life (non-preferred) (ii) GB 8735 – early maturity (80 days) and good seed fill (preferred) and susceptibility to pests (non-preferred) (iii) LCIC 9702 – early maturity (75 days), compact head (preferred) and sensitive to downy mildew (non-preferred) (iv) ZATIB – medium maturity (95 days), compact head (preferred) and sensitive to stem borers (non-preferred).

Various factors were responsible for adoption of modern varieties, which included knowledge of the varieties, education level of the family head, number of traditional varieties known and pearl millet cultivated area. The impact of modern varieties on different aspects of livelihoods such as per capita gross income, per capita value of production and household average pearl millet yield was higher by 34 to 76 %, 48 to 101 % and 88 kg/ha to 157 kg/ha, respectively, for adopters compared to non-adopters. Furthermore, the adopters produced 127 kg/person/year to 230 kg/person/year cereals more than non-adopters. However, there were no significant differences between adopters and non-adopters with respect to the number of hungry months, per capita wealth or per capita expenditure, indicating that probably the modern varieties had limited impact on poverty alleviation. Overall, the current adoption rate of modern pearl millet varieties is only ~35 % whereas the probability of adoption is ~59 % i.e., a gap of 24 %. Increased awareness coupled with promotion of best performing varieties such as SOSAT C88 would be likely to increase the adoption of modern pearl millet varieties.

Pearl millet as a nutritious food crop

Protein and amino acid content

The protein content of pearl millet grain ranges from 8 to 24 % (Hulse et al. 1980; Rooney and McDonough 1987) and the in vitro protein digestibility (IVPD) from 60.5 % to 76.9 % (Elyas et al. 2002, Ali et al. 2003). A significant increase of IVPD from 72.7 % to 83.6 % upon fermentation [14 h] was reported by Hag et al. (2002). Seed germination and dehulling have also been reported to improve protein digestibility from 54 % to 78 % (Hag et al. 2002; Kumar and Chauhan 1993). The amino acid profile of pearl millet grain is shown in Table 5. A wider range of lysine, an essential amino acid, has been reported in pearl millet [1.7–6.5 g/100 g protein] than other millets such as proso millet [1.4–4.3 g/100 g], foxtail millet [1.5–2.8 g/100 g], and kodo millet [*Paspalum scrobiculatum*; 3.0–3.5 g/100 g] (McDonough et al. 2000). The majority of the cereals consumed worldwide have similar amino acid profiles

Table 4 Five year average of grain yield and increment in yield over mean grain yield of base period 1989–93 of major food crops in India during 1989–2013

Period	Grain Yield (kg/ha)					Yield Improvement (%) over Yields of 1989–1993				
	Rice	Wheat	Maize	Sorghum	Pearl Millet	Rice	Wheat	Maize	Sorghum	Pearl Millet
1989–93	1773.6	2300.6	840.8	1560.8	618.0	-	-	-	-	-
1994–98	1882.2	2559.2	823.0	1678.6	737.0	5.8	10.1	−2.2	7.0	16.2
1999–03	1957.6	2714.2	770.4	1867.2	791.6	9.4	15.2	−9.1	16.4	21.9
2004–08	2119.4	2727.6	900.8	2101.2	920.8	16.3	15.7	6.7	25.7	32.9
2009–13	2328.6	3039.2	908.4	2438.6	1068.6	23.8	24.3	7.4	36.0	42.2

Source: Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Government of India

except for lysine, tryptophan, tyrosine, leucine and isoleucine. Tyrosine content in pearl millet [2.4 g/100 g protein] is lower than in rice [3.7 g/100 g protein], maize [3.9 g/100 g protein] and sorghum [4.2 g/100 g protein], but comparable to barley (2.8 g/100 g protein; Ejeta et al. 1987). The content of the essential amino acid tryptophan and isoleucine in pearl millet is comparable or lower than in other millets and sorghum (McDonough et al. 2000; FAO 1995).

Fat content and fatty acid profile

The fat content of pearl millet grain [4.7 %] is significantly higher than that of rye (*Secale cereale* L.; [1.5 %]), wheat [1.9 %] (Alais and Linden 1991) and sorghum (3.32 %; Ragaee et al. 2006), but, lower than that of oats (*Avena sativa* L.; 5.9 %; Alais and Linden 1991). Pearl millet grain contains polyunsaturated fatty acids (PUFA; ~50 %), monounsaturated fatty acids (MUFA; ~ 25 %) and saturated fatty acids (~25 %; SFA; Table 6). Pearl millet is a good source of unsaturated fatty acids such as linoleic acid (~45 %; PUFA) and oleic acid (25 %; MUFA) (Sawaya et al. 1984). Though linoleic acid content in pearl millet is relatively high, sorghum and maize have higher percentage (49 % and 56 % respectively) of this PUFA (Rooney 1978). Oleic acid content is comparable in corn and pearl millet [25 %] and higher in sorghum [31 %]. Linolenic acid (PUFA) and stearic acid (SFA) are the two minor fatty acids present in pearl millet oil (Table 6). Pearl millet has a higher percentage of palmitic acid (SFA) content compared to corn [12.7 %] and sorghum [14.3 %].

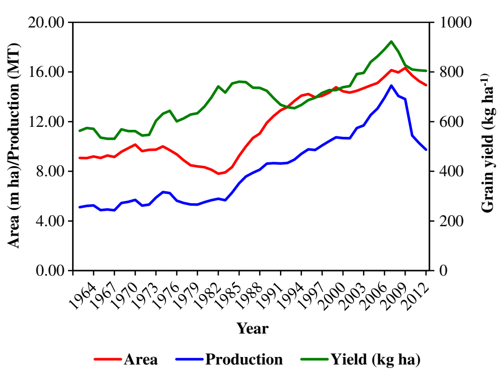


Fig. 6 Three-year moving average for pearl millet area, production and grain yield for West and Central Africa. *Source*: FAOSTAT 2015 (http://faostat3.fao.org/download/Q/QC/E)

Carbohydrates and dietary fibre

Total carbohydrate content of pearl millet [55.3–75.4 g/100 g] is similar to or lower than other cereals such as maize [70.5–78.6 g/100 g] or sorghum (59.0–82.5 g/100 g; Barikmo et al. 2004). Total soluble sugar content in pearl millet ranges between 1.4 and 2.78 % (McDonough et al. 2000). Sucrose and raffinose constitute about 63 % and 29 % of total sugars, respectively, in pearl millet (McDonough et al. 2000). The range of different sugars in pearl millet grain includes sucrose [1.32–1.82 g/100 g], raffinose [0.65–0.84 g/100 g] and stachyose (0.06–0.13 g/100 g; FAO 1995). Hadimani et al. (2001) reported the presence of other sugars such as arabinose and xylose [0.02–0.30 g/100 g], galactose [0.01–0.11 g/100 g] and glucose [0.36–3.65 g/100 g]. Starch content in pearl millet varies from 65.8–75.3 % (Hadimani et al. 2001) and is higher [69.0 %] than that of other millet crops such as proso/foxtail millet [~60.0 %], kodo millet [54.9 %], barnyard millet [57.0 %], and comparable to finger millet [65.5 %] (Malleshi and Desikachar 1986). Germination up to 96 h results in ~10 % loss in starch content in pearl millet. Total amylose content of different pearl millet cultivars was reported to be 27–32 % (Hadimani et al. 2001). Starch granules in pearl millet are polygonal in shape and their size ranges from 3.5–16.0 μm (Hadimani et al. 2001).

Dietary fibres (DF) are classified into: (i) soluble DF (SDF) - digested slowly in the colon and (ii) insoluble DF (IDF) - metabolically inert and aid in bowel movement (Tosh and Yada 2010). Total dietary fibre (TDF) content of pearl millet [14.95 %] though higher than wheat [4.59 %] is comparatively lower than barley [24.6 %], sorghum and rye [17.8 %] (Ragaee et al. 2006). However, a higher TDF [20.4 %] for pearl millet was reported by Kamath and Belavady (1980).

Table 5 Amino acid content (g/100 g protein)* in pearl millet grain

Amino Acid	Burton et al. 1972	Bailey et al. 1979	Ejeta et al. 1987
Lysine	2.6–3.7	2.0–3.6	2.8
Methionine	2.1–2.5	1.6–2.6	2.3
Cystine	1.3–2.1	1.5–2.2	1.2
Phenylalanine	3.7–4.9	5.0–5.9	5.6
Tyrosine	-	2.0–4.0	2.4
Isoleucine	4.3–5.0	3.3–5.0	4.4
Leucine	9.3–17.4	9.1–11.3	11.5
Threonine	3.4–4.9	3.0–4.4	4.2
Valine	5.4–5.7	4.2–6.1	6.0
Arginine	4.7–7.5	2.6–5.1	3.9
Histidine	2.1–2.6	1.2–2.0	2.4
Alanine	-	7.5–8.9	8.8
Aspartic acid	-	7.7–8.9	8.7
Glutamic acid	-	17.6–20.0	22.1
Glycine	-	2.5–3.9	3.2
Proline	-	6.2–7.3	6.8
Serine	-	4.9–5.5	5.3
Tryptophan	1.4–2.3	3.0–4.7	-

* Equivalent to g/16 g N

IDF content in pearl millet is lower than that of barley, rye and sorghum, and the SDF fraction is lower than that of barley and rye (Ragaee et al. 2006). Digestion resistant starch content in grains of pearl millet and sorghum is 1.96 % and 1.77 %, respectively, while other cereals (wheat, barley, and rye) contain <1.0 % RS (on dry basis) (Ragaee et al. 2006).

Minerals

Pearl millet's mineral profile is presented in Table 7. Phosphorus (P), potassium (K) and magnesium (Mg) are the major mineral constituents of pearl millet grain. High 'P' content [450–990 mg/100 g] in pearl millet grains was reported by

Table 6 Fatty acid composition of pearl millet grain

Fatty Acid	Jellum and Powell 1971 (%)	Rooney 1978 (%)	Lai and Varriano-Marston 1980	
			% Free Lipids	% Bound Lipids
Capric (C10:0)	-	-	-	0.7–3.4
Lauric (C12:0)	-	-	-	0.7–3.2
Tridecanoic (C13:0)	-	-	-	0.3–0.6
Myristic (C14:0)	-	-	Trace-0.2	0.4–0.8
Pentadecanoic (C15:0)	-	-	-	0.3–1.3
Palmitic (C16:0)	16.7–25.0	19.0	20.7–21.6	21.0–23.2
Palmitoleic (C16:1)	-	0.6	0.9–1.1	0.8–1.4
Margaric (C17:0)	-	-	-	0.2–0.5
Stearic (C18:0)	1.8–8.0	5.0	6.1–10.1	4.8–7.9
Oleic (C18:1)	20.2–30.6	25.0	27.2–28.2	16.6–19.5
Linoleic (C18:2)	40.3–51.7	46.0	36.7–39.8	26.6–32.3
Linolenic (C18:3)	2.3–5.8	3.2	2.2–4.2	1.9–3.3
Arachidic (C20:0)	-	0.5	0.8–1.2	5.1–7.8
Behenic (C22:0)	-	-	Traces	-
Lignoceric (C24:0)	-	-	-	5.0–8.0
Unknown	-	-	-	0.6–1.3

Table 7 Mineral content (μg/g) in pearl millet grain

Mineral	Bailey et al. 1979	Varriano-Marston and Hoseney 1980	Abdalla et al. 1998
Calcium	17.0–34.0	65.0–132.0	10.0–80.0(*)
Magnesium	5.0–15.0	1167.0–1557.0	180–270.0(*)
Iron	1.0–6.0	61.0–83.0	70.0–180.0
Potassium	370.0–860.0	3666.0–5106.0	70.0–110.0
Phosphorus	420.0–890.0	66.5–95.1	-
Copper	8.6–21.0	-	10.0–18.0
Zinc	2.6–13.1	23.0–38.0	53.0–70.0
Manganese	7.2–22.0	-	18.0–23.0
Sodium	-	20.0–49.0	4.0–13.0
Bromine	10.0–19.0	-	-
Chromiuim	-	-	-
Strontium	19.0–71.0	-	-
Titanium	3.4–13.1	-	-

(*) -mg/100 g

Abdalla et al. (1998). The percent of phytic acid to total 'P′ in pearl millet genotypes was ~70–89 %, with an average value of 77 % (Abdalla et al. 1998). The percentage phytin 'P′ (phytic acid bound to cations) of the total phosphorus content in cereal grains is reported to be ~33–90 % (Hamdy 1971). Total content of 'Mg′ in pearl millet was higher than that in maize (93.8 mg/100 g; Adeola and Orban 1995). Pearl millet had higher content of 'Mg′ (1488 mg/kg)/and 'K′ (2798 mg/kg) compared to wheat (301.2 & 826.2 mg/kg) or sorghum (187.7 & 239.9 mg/kg) but lower than barley (1971 & 4572 mg/kg) (Ragaee et al. 2006). Calcium [Ca] content in pearl millet [~500 mg/kg] was reported to be similar to other cereals (Burton et al. 1972), but the bioavailability of 'Ca′ was low (27–32 %; Abdel Rahman et al. 2005).

Vitamins

Pearl millet is rich in B-vitamins but does not contain vitamin C (Nambiar et al. 2011). The concentration of different vitamins in pearl millet grain is: thiamine (B1; 0.27–0.38 mg/100 g), riboflavin (B2; 0.15–0.25 mg/100 g), pyridoxine (B6; 0.27), niacin [0.89–2.7 mg/100 g], folic acid [34.9–45.5 μg/100 g] and pantothenic acid (1.09–1.40 mg/100 g; Khalil and Sawaya 1984; Léder 2004; Nambiar et al. 2011). These vitamins are concentrated in aleurone and germ layers. Decortication reduces the content of niacin, riboflavin and thiamine by ~50 % (Nambiar et al. 2011). β-carotene content in pearl millet cultivars is very low, but improved varieties are slightly better [0.133 μg/kg] or comparable to landraces [0.091 μg/kg] and hybrids [0.103–0.114 μg/kg] (Buerkert et al. 2001). In general, pearl millet cannot be considered a good source of β-carotene since it provides <0.3 % of recommended dietary allowance (RDA; Khalil and Sawaya 1984; Desai and Zende 1979).

Anti-nutritional factors (ANFs)

The content of ANFs in pearl millet is lower compared to other cereals (Andrews and Kumar 1992). Elyas et al. (2002) reported tannins in pearl millet at 0.12 %-0.24 % expressed as catechin equivalents (CE). Pearl millet contains different phenolic compounds including phenolic acids, and flavonoids (flavones). Total phenolic acid content in pearl millet grain has been reported to be about 147.8 mg/100 g (Dykes and Rooney 2007), but another study has reported a higher range of 294–314 mg/100 g (Elyas et al. 2002). Pearl millet also contains gentisic [96.3 μg/mg], coumaric [268.2 μg/mg], ferulic [679.7 μg/mg] and cinnamic [345.3 μg/mg] acids (Dykes and Rooney 2006). Flavones present in grain are also referred to as C-glycosylflavones and their content varies between 87 and 259 mg/100 g of C-glycosylflavone expressed as glycosylvitexin equivalents (Reichert et al. 1980). Different tocols such as α-tocopherol [1.3 mg/kg], γ-tocopherol [55.4 mg/kg], δ-tocopherol [0.8 mg/k]), γ-tocotrienol [5.3 mg/kg] and δ-tocotrienol [2.0 mg/kg] have also been reported in pearl millet (White and Xing 1997).

Phytic acid typically represents 65–85 % of total grain 'P′ in crops (Raboy 1990, 1997). Phytic acid readily forms complexes with multivalent cations and proteins thereby affecting the bioavailability of nutrients. Phytic acid content in pearl millet varied between 172 and 327 mg/100 g (Sankara Rao and Deosthale 1983, Chauhan et al. 1986). But, Abdalla et al. (1998) and Elyas et al. (2002) reported 354–796 mg/100 g and 393–786.2 mg/100 g, respectively; further, even higher levels of up to 990 mg/100 g were observed by Khetarpaul and Chauhan (1991). During germination, phytase, an enzyme that breaks down phytic acid is produced, due to which the bound minerals are made available (Geetha et al. 1997). Pearl millet exhibited varietal specific inhibitory activity against α-amylase (Chandrasekher et al. 1981) and trypsin (Chandrasekher et al. 1982). The trypsin and amylase inhibitory levels of pearl millet were 7.3 U and 80.2 U respectively (Osman 2011). ANFs act as limiting factors in pearl millet consumption but their content can be decreased or eliminated by processing (soaking, cooking, and boiling) as explained above. Additionally, ANFs have certain potential health benefits (see below).

Health benefits

Increasing awareness of health and nutrition issues necessitates research on alternative crops such as millets for their potential health benefits. Some research findings indicate the beneficial effects of the chemical composition of pearl millet grain.

Cancer

Phenolic extracts of pearl millet grain exhibited a range of anti-carcinogenic effects including: (i) highest scavenging activity (25 %) against singlet oxygen among different millets at 1 mg/ml (ii) reduced the ultraviolet light (UVA)-induced liposome peroxidation by 80 % at 1 mg/ml (Chandrasekara and Shahidi 2011c) (iii) inhibited DNA scission induced by hydroxyl and peroxyl radicals by about 60 % at 0.5 mg/ml millet extract (Chandrasekara and Shahidi 2011c). But, higher rates of inhibition by pearl millet grain extracts [at 0.5 mg/ml] for peroxyl [31–88 %] and hydroxyl [67–89 %] induced DNA scission were also reported (Chandrasekara and Shahidi 2011a). Further, time and dose dependent suppression [by 40 %] of HT-29 human colon adenocarcinoma cells by pearl millet extracts at 0.1 mg/ml (Chandrasekara and Shahidi 2011c). Soluble extracts of pearl millet contain flavonoids such as quercetin, luteolin, vitexin, isovitexin and apigenin (Chandrasekara and Shahidi 2011b) which could be used as potential chemo-preventive agents in prevention of carcinogenesis (Chandrasekara and Shahidi 2011a). Antiproliferative activity of different phenolic acids against 747 D human breast cancer cells was reported to be in the following order: caffeic > trans ferulic > sinapic = syringic (Kampa et al. 2004). Ferulic acid [679.7 μg/mg], caffeic acid [21.3 μg/mg] and syringic acid [17.3 μg/mg] content of pearl millet is higher than other millets (Dykes and Rooney 2006).

Coronary heart disease

Consumption of fibre-rich food results in reduction of total serum cholesterol/low density lipoprotein-cholesterol (LDL-C) and this is related to decreased occurrence of coronary heart disease-related mortality (Jukanti et al. 2012). Further, oxidation of LDL-C plays a key role in atherosclerosis (Esterbauer 1993). Pearl millet whole grain bound phenolic extracts inhibited the oxidation of copper-catalyzed LDL-C by 33 % at a concentration of 50 μl/ml (Chandrasekara and Shahidi 2011a). Chelation of cupric ions and scavenging of peroxyl radicals by millet phenolics could be responsible for inhibition of oxidation of LDL-C. The high caffeic acid content in pearl millet grains (Chandrasekara and Shahidi 2011b) and synergistic effect of different phenolic compounds could be effective in the inhibition of LDL-C oxidation (Nardini et al. 1995).

Celiac disease

Celiac disease is an intestinal disorder (chronic inflammation of small intestine) that is caused by an immunological reaction to gluten (present in cereals such as wheat, barley and rye; Johari et al. 2015). As there are no drugs or cure for patients with celiac disease, the only option for a normal, healthy lifestyle is to consume a gluten free diet. Pearl millet is ideal for celiac disease patients as its grain is gluten-free. There is an increasing demand for gluten-free foods and beverages from people with intolerances to wheat, barley, or rye. As pearl millet is gluten-free it has considerable potential in foods and beverages suitable for individuals suffering from celiac disease.

Grain processing technologies and value addition

Several technologies for processing pearl millet grain can reduce anti-nutritional factors (Tables 8 and 9), increase shelf life and digestibility (NFSM 2014). For instance, dehulling decreases fibre, ash, fat, protein and micro-nutrient content, but it improves the quality and sensory properties of the products. Moist heating (heating, drying and decortication) improves the milling properties of pearl millet, increases shelf life of flour (3–4 months) and reduces the microbial load on the grain surface. Malting reduces protein content but improves its quality. Further, it improves bioavailability of minerals, increases vitamins and decreases polyphenols and

Table 8 Reduction in polyphenols and phytic acid due to different processing technologies

Treatment	Anti-nutrients (mg/100 g grain)	
	Polyphenols	Phytic Acid
Untreated (control)	755	858
Malting (48 h)	449	481
Blanching	529	565
Acid Treatment (24 h)	182	153

Source: Rekha 1997; Poonam (2002)

Table 9 Impact of acid and heat treatment on fat acidity, free fatty acids and lipase activity in pearl millet flour

Rancidity factor	Storage Period (days)				
	0	7	14	21	28
(I) Fat acidity (mg KOH/100 g flour)					
Control	30.3	42.4	58.1	83.3	123.7
Acid treatment	35.1	35.0	36.2	38.6	38.0
Heat treatment	28.0	30.9	34.4	41.2	50.5
(II) Free fatty acids (mg/100 g fat)					
Control	282.0	427.3	789.0	942.0	1115.0
Acid treatment	208.0	210.3	216.0	221.0	230.3
Heat treatment	67.0	70.0	75.0	80.0	84.0
(III) Lipase activity (% enzyme activity on % fat)					
Control	3.7	5.6	10.3	12.4	14.6
Acid treatment	2.9	2.9	3.0	3.1	3.2
Heat treatment	0.9	0.9	1.0	1.1	1.1

Source: Adapted from Rai et al. 2008

phytic acid levels (Table 8). Blanching (soaking grains in boiling water, 1:5 of seeds to water for 30 s followed by drying at 50 °C for an hour) is very effective in improving the shelf life of flour and retarding the development of fat acidity. Acid treatment (treating decorticated seeds with mild acids such as acetic acid) improves the product quality by reducing polyphenols and phytic acid. Acid treatment also increases in vitro protein digestibility. Dry heat treatment reduces lipase activity and minimizes lipid decomposition during storage (Table 9). Parboiling helps in decortication of grain. Parboiled-decorticated grains are mostly used for various snacks, especially for diabetics. These technologies have been reviewed and summarized elsewhere (Rai et al. 2008).

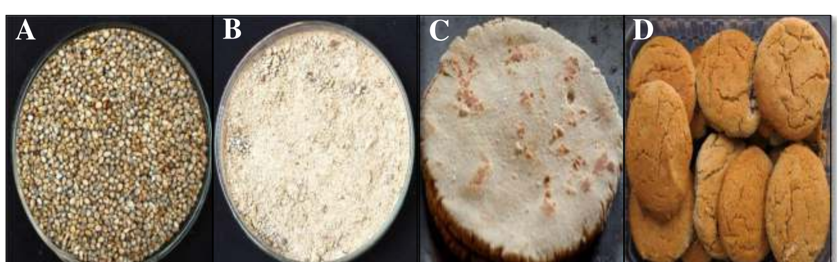
Different processed food products are prepared from pearl millet flour (Yadav et al. 2012). Traditional foods such as porridge or flat and unfermented bread (chapatti) are commonly prepared from pearl millet flour (Fig. 7). Preparations from processed pearl millet flour contain lower content of anti-nutrients and are more easily digested (Singh 2003). Furthermore, in India, several snacks (*sev*, *laddoo*, *namkeen* and *matari*) with good shelf life are prepared from pearl millet.

In addition to these traditional foods, pearl millet is also a good raw material for the bakery industry. Pearl millet cookies produced with some supplements have spread characteristics (texture, grittiness and top grain) on a par with those made from wheat flour. Different types of biscuits and cakes with good organoleptic qualities are being produced from pearl millet flour (either blanched or malted; Singh 2003). Pearl millet flour can also be used to prepare ready-to-eat (RTE) products. Extrusion (cooking at high temperature for a short time) is being used to prepare RTE products which have better digestibility and probably inactivated anti-nutritional factors. Pearl millet products prepared from blends of different flours (such as gram or soybean) have better protein content and protein efficiency ratio (Sumathi et al. 2007).

Though flaking is a new avenue for pearl millet, initial exploratory experiments have been promising (Yadav et al. 2012). Similarly, popping of pearl millet is also not common, but popped pearl millet has better nutritional quality. As popped millet is a good source of energy, fibre and carbohydrates it is utilized in producing supplementary or weaning foods for children. Malting helps in the production of easily digestible, high calorie and low viscous weaning foods, essential during the transition of infants from breast feeding to other type of foods. Pearl millet's high fibre content, gluten-free nature coupled with its relatively good nutritional composition (see below) makes it the cereal of choice for preparing various kinds of health foods. Pearl millet flour is also used to prepare different kinds of drinks such as *rab*/*rabari* (Rajasthan), '*Cumbu Cool*' (Tamil Nadu), *lassi* and buttermilk.

Diabetes and satiety

A lower glycemic index (GI) value [55] was recorded for pearl millet compared to white rice [69] but higher than most of the grain legumes [20–40] (Foster-Powell et al. 2002). Lower GI values for pearl millet [55 ± 13] than sorghum [77 ± 8], finger millet [104 ± 13], kodo millet [68 ± 8] and kodo millet + mung bean dal (*Phaseolus* sp.; 78 ± 12) have been observed (Mani et al. 1993). Blood glucose response (in mg/dal) after consumption of these foods (50 g) at 2 h postprandial levels revealed significant differences between these groups: pearl millet [240 ± 41], sorghum [275 ± 36], finger



A – grain, B – flour, C – flat bread, D – biscuits

Fig. 7 Products prepared from pearl millet grain. *Source*: Central Arid Zone Research Institute, Jodhpur, India; **a** – grain, **b** – flour, **c** – flat bread, **d** – biscuits millet [251 ± 34], kodo millet [251 ± 40] and kodo millet + mung bean/greengram dal [239 ± 38]. The hypoglycaemic effect is usually observed with low GI foods such as legumes (high fibre content) and pearl millet (has lower fibre content compared to legumes). Therefore, it is understood that pearl millet additionally contains other factors that moderate its GI value. Further, consumption of low-GI foods delayed hunger for the next meal and had higher satietogenic effects compared to high GI foods (Bornet et al. 2007). Therefore, due to its lower GI value pearl millet could potentially be used in managing hyperglycaemia in diabetic patients, and to some extent in reducing obesity.

Future prospects

Limited sustainable and cost-effective options are available to farmers of arid and semi-arid regions to shift from pearl millet to other remunerative crops. Suitable, low-cost improved technologies are required by smallholder farmers of these regions to sustain and increase production and productivity of pearl millet. Farmers need high-yielding cultivars, especially hybrids, with good grain and forage quality, which are preferred by farmers and consumers. Crop improvement efforts need to be continued for developing cultivars with high yield potential, tolerance to important abiotic stresses and resistance to major biotic stresses incorporating both conventional breeding and advanced molecular tools and techniques. High soil salinity in pearl millet production regions is another priority area. Some preliminary work on salinity tolerance has been initiated by ICRISAT in collaboration with the International Center for Biosaline Agriculture (ICBA), Dubai and NARS partners in India and West and North Africa. The yield of hybrids and OPVs can be further increased substantially by using improved crop management techniques.

Malnutrition is a major concern in the majority of the pearl millet growing regions of Asia and Africa. Therefore, breeding efforts should be directed towards developing varieties/hybrids with good nutritional quality (eg. iron and zinc content). Another priority area generally suggested is the development of cultivars with lower phenolic compounds, slightly lower fat content, and increased shelf life and keeping quality of flour (Nagaraj et al. 2012). However, incorporation of these traits in breeding could lead to a slowdown in genetic improvement for other high priority traits. These traits could better be handled by application of various processing technologies, which need to be tested for their applications at household, community and industrial scales. Pearl millet cultivars with improved nutritional content could be a good source of foods with potential health benefits and nutraceutical value as well as for the production of grain-based ethanol, provided its carbohydrate (starch) content is increased to 65 % from the present level of 55 % (Nagaraj et al. 2012). Varieties/hybrids with high starch content could very well complement maize, rice and other crops for alcohol production. Value-addition in pearl millet is crucial to the generation of market demand for grains and could make this crop profitable for producers. There is a huge potential for bakery products (bread, biscuits, cookies etc.), extrusion products, nutraceuticals, and health promoting foods. Besides developing better varieties, improvement in agronomic management technologies is also required. It is obvious from the above discussion that there is considerable scope for investing in different technologies which will have a trickle-down effect for the betterment of conditions of dryland farmers who cultivate and consume pearl millet.

Conclusion

Unlike other cereal crops such as rice, wheat, maize and barley, which have been extensively used for food and industrial purposes, pearl millet has mostly remained a food crop with limited novel foods and industrial uses. Productivity has been low, particularly in sub-Saharan Africa, owing to harsh environmental conditions, lack of availability of seed of improved cultivars, and inability of poor smallholder farmers to adopt improved crop management technologies. Therefore, increase in pearl millet productivity will have a direct impact on reducing poverty and increasing food security. Development and adoption of high-yielding cultivars and cost effective crop management/production technologies will have a significant impact on the livelihoods of the dryland farmers of Asia and sub-Saharan Africa. Additionally, pearl millet is also a nutritionally rich crop which can play a role in improving nutrition and health. Pearl millet is an affordable source of carbohydrates, proteins, minerals, vitamins and other important bioactive compounds necessary for human growth and development. The literature provides some evidence supporting the health promoting benefits of pearl millet, but information pertaining to the role of individual components of the plant in disease prevention is limited. Overall, pearl millet with its hardiness and good prospects of genetic enhancement has the potential of contributing to sustainable food and nutritional security of farmers in the arid and semi-arid tropics, and other parts of the world with similar agro-ecologies.

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