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Global Production, Status, and Utilization Pattern of Pearl Millet

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Chapter Overview

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is a major cereal and staple food in the developing world, especially in the arid and semi-arid regions of Asia and Africa. It is cultivated on >30 million ha in the arid and semi-arid tropical regions of Asia and Africa, contributing 40.51% of the global millet production, with 60% of the cultivation area in Africa and 35% in Asia. It is primarily cultivated for grain production, but its stover is also valued as dry fodder. It is resilient to climate change due to its inherent adaptability to drought and high temperatures and is well adapted to marginal lands with low productivity. In addition, it has several nutritional properties and is rightly termed as nutricereal. It has high levels of energy, dietary fiber, and proteins with a balanced amino acid profile, many essential minerals, some vitamins, and antioxidants, which help in combating several diseases. Due to its excellent properties, it can play a vital role in overcoming malnutrition to ensure food and nutritional security. The different efforts being taken up to enhance its production and consumption on a global scale will be highly useful in the present scenario to overcome the challenges of the growing population. Thus, 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 agroecologies.

Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is the sixth major cereal crop globally, followed by maize, rice, wheat, barley, and sorghum. It is cultivated on

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>30 million ha in the arid and semi-arid tropical regions of Asia and Africa, contributing 40.51% of the global millet production, with 60% of the cultivation area in Africa and 35% in Asia (FAO, 2020). This crop is widely used as a staple food for human consumption and as fodder and feed for livestock. Additionally, it is used in various industries, such as alcohol fuel, starch, and the processed food sectors. Pearl millet is imperative to mitigate the adverse effects of changing climate and can provide income and food security to the farming communities of arid regions. In India, it is the fourth most commonly grown food crop, after rice, wheat, and maize. It shows rapid growth with minimal inputs, high photosynthetic efficiency, a balanced and good nutritional profile, and tolerance to extreme climatic conditions and biotic stresses.

Pearl millet is a hardy crop that can thrive in adverse agro-climatic conditions. It can withstand low soil fertility, high soil pH, high soil Al^{3+} saturation, low soil moisture, high temperature, high soil salinity, and low rainfall, making it a viable option in areas where other staple cereal crops like rice and wheat struggle to survive. As per the fourth advance estimates during 2021–2022, the pearl millet area in India was 6.70 million ha, with an average production of 9.62 million tons and productivity of 1,436 kg/ha (Directorate of Millets Development, 2024). The major pearl millet growing states in India are Rajasthan, Maharashtra, Uttar Pradesh, Gujrat, and Haryana, contributing to 90% of total production in the country. Rajasthan contributes nearly 45%, followed by Uttar Pradesh (19%), Haryana (9%), Gujarat (9%), Maharashtra (6%), and Tamil Nadu (2%). Most pearl millet in India is grown in the rainy (*kharif*) season (June/July–September/October). Pearl millet is also cultivated during the summer season (February–May) in parts of Gujarat, Rajasthan, and Uttar Pradesh and during the post-rainy (*rabi*) season (November–February) at a small scale in Maharashtra and Gujarat.

Pearl millet is more nutritious than commonly consumed staple crops such as wheat, rice, maize, and sorghum. Its grain is rich in carbohydrates, proteins, fats, fibers, resistant starch (RS), vitamins, antioxidants, and essential micronutrients like Fe and Zn and has a more balanced essential amino acid profile than maize or sorghum. It also contains omega-3 and omega-6 fatty acids (polyunsaturated fatty acids), which are good for heart and brain health. Despite being less expensive than pearls, pearl millet offers pearl-like quality that is advantageous to the body: 100 g of grain contains 360 calories, 12 g moisture, 12 g protein, 5 g fat, 2 g minerals, 1 g fiber,67 g carbohydrates, 42 mg Ca, 242 mg P, and 8 mg Fe. It is a gluten-free grain with high-quality protein, making it ideal for those with gluten allergies. It is the only cereal that retains its alkaline nature after cooking and has a low glycemic index (GI), making it a diabetic-friendly food. It acts as a probiotic food for microflora in our inner ecosystem and hydrates our colon preventing constipation. Its consumption has been associated with protection against certain types of cancer and cardiovascular diseases. It has high proportions of slowly digestible starch and

RS, which contribute to its low GI, and is much sought after in the recent era of transforming diets, eating habits, and the food industry. As a result, pearl millet is gaining popularity among health-conscious people worldwide.

Pearl millet can play a vital role in overcoming malnutrition to ensure food and nutritional security. Due to its excellent nutritional properties, pearl millet is designated as a "nutri-cereal" (Gazette of India, No. 133 dtd 13th April, 2018) for production, consumption, and trade and was included in the public distribution system. India's prime minister has given it the name of "Shree Anna" for its superior quality over all other grains. In addition, to include millets in the mainstream and to exploit their nutritionally superior qualities and promote their cultivation, the Government of India declared 2018 as the "Year of Millets," and the FAO Committee on Agriculture forum declared 2023 as the "International Year of Millets."

Pearl millet is the next-generation crop holding the potential of nutritional richness and climate resilience. To fully tap into its potential, efforts must be made to enhance its production and consumption on a global scale. The availability of high-quality whole genome sequences and re-sequencing information will provide a good opportunity for genomic dissection and for exploiting the nutritional and climate-resilient attributes of pearl millet. Additionally, an integrated approach that includes genomics, transcriptomics, proteomics, and metabolomics can provide valuable insights into the genetic improvement and biofortification of pearl millet (Ambawat et al., 2020; Anuradha et al., 2017; Dita et al., 2006; Lata, 2015). There is a need to focus on this very important crop and harness its suitability to adverse conditions and to use its capacity to ensure global food and nutritional security. Therefore, we must continue to make advances in the pearl millet improvement program and prioritize this vital crop in the face of changing climatic conditions to ensure food and nutritional security.

History of Pearl Millet: Origin and Spread

Pearl millet originated in tropical Western Africa around 4,000 years ago. It is a member of the grass family and was originally a wild plant in Africa, where the largest members of both wild and cultivated forms of this species occur. Later, it differentiated into two races: the *globosum* race, which moved to the western side, and the *typhoides* race, which reached Eastern Africa and spread to India and Southern Africa around 2,000–3,000 years ago. Due to its evolution under drought and high temperatures, pearl millet can tolerate harsh conditions in Indian and African deserts better than other cereals, such as wheat and rice (Sheahan, 2014). Based on crossability, cross fertility, and the complexity of gene transfer studies of *Pennisetum* species, three gene pools were classified: primary, secondary, and tertiary (Harlan & De-Wet, 1971). All types of weedy, cultivated, and wild diploids ($2n = 2x = 14$) were included in primary gene pool. The secondary gene pool was comprised exclusively of tetraploid *P. purpureum* (Shum.) ($2n = 4x = 28$), and the tertiary gene pool contained widely related *Pennisetum* species of different ploidy levels (Dujardin & Hanna, 1989).

Unlike in the primary gene pool, where hybridization among species results in fertile hybrids, gene transfer from the secondary and tertiary gene pools is not straightforward due to genetic incompatibilities. For that, introgression is carried out via embryo rescue–assisted techniques under artificially controlled conditions. Producers are reluctant to work in the pre-breeding sector due to the long breeding cycles required for isolating desired segregants, the low hybrid seed set, seed sterility, the large advanced population size required for selection, and the maintenance of wild germplasm. Earlier pearl millet researchers concentrated on identifying and utilizing traits donors available in cultivated pearl millet and its primary gene pool. A study of 529 wild pearl millet species, consisting of *P. violaceum*, *P. mollissimum*, *P. purpureum*, *P. pedicellatum*, and *P. polystachyon* under artificial and field conditions, identified 223 accessions with no disease symptoms (Singh & Navi, 2000). Crosses with two wild species (*P. pedicellatum* and *P. polystachion*) attempted to introgress downy mildew resistance, but no seed set was noted in the hybrids formed (Dujardin & Hanna, 1989).

Commercial Uses

Pearl millet is a versatile crop that serves as a staple food for humans and as a source of feed for livestock. Its different uses in different parts of the world are summarized in Table 1.1. It is used in industries such as—alcohol, fuel, starch and processed food sectors. Around 90 million people in the Sahelian region of Africa and northwestern India consume pearl millet grain as a primary source of food (Jukanti et al., 2016; Srivastava et al., 2020). It is used in different forms at the global level, such as unleavened bread (roti or chapatti), porridge, gruel, dessert, and is generally defined as a "poor man's bread." Its flour can substitute (10%–20%) for wheat flour in whole-grain breads, pretzels, crackers, tortillas, and dry and creamed cereals (Dahlberg et al., 2003). Although it is mainly grown for food and forage in India and Africa, it serves as a major component of poultry and livestock feed in the American continent (Serba et al., 2020). Pearl millet can be used as a quality-protein grain for many livestock-feeding purposes. It has higher crude protein, essential amino acids, and ether-extract concentrations in comparison to maize and thus can prove more promising for feeding poultry and cattle. In addition to being grown for grain, pearl millet is also cultivated as a forage crop for livestock grazing, silage preparation, hay production, and the cutting of green

Table 1.1 Utilization Pattern of Pearl Millet in Different Parts of the World.

Site no.	Country/city	Use	Popular names of items
1	India	Industries	Alcohol and fuel
		Forage and grain	Livestock and poultry feed
		Traditional food products	Roti or chapatti, rabri, dalia, gruel, kheer, churma, suhaali, khichri, sakarpare, gulgule, mathi, ladoo, barfi, sev, pakoda, dhokla
		Baked products	Biscuits, bread, cookies, cakes, puffs, muffin, nan-khatai
		Extruded products	Noodles, pasta, vermicelli, macroni
		Health products	Sugar free biscuits, idli
2	West Africa/ Sahelian region	Industries	Non-alcoholic or alcoholic beverages
		Forage and grain	Livestock and poultry feed
		Food products	Stiff or thick porridges (Tuwo or Tộ)
3	Senegal	Steam-cooked products	Couscous, thin porridge (*bouillie*)
4	Nigeria and Niger	Food products	Porridge (*Fourra*) and fried cake (*Masa*)
5	Senegal	Food products	Soungouf; "Sankhal" and "Araw"

fodder (Newman et al., 2010). The advantage of using this crop as livestock feed is that it may be fed to animals at any stage of crop development without negative consequences (Arya et al., 2013). This has been practiced in the countries like the United States (Sheahan, 2014), during the summer in Australia (Hanna, 1996), Canada (Brunette et al., 2014), and Mexico (Urrutia et al., 2015). It is also used as triple cropping method in southern Kyushu, Japan (Li et al., 2019); Iran (Aghaalikhani et al., 2008); Central Asia (Nurbekov et al., 2013); and Brazil (Dias-Martins et al., 2018). It has become a significant fodder crop in northwest India during the summer (Amarender Reddy et al., 2013) and recently has been used as a cover crop in Brazil (5 million ha) (De Assis et al., 2018; Dias-Martins et al., 2018). Climate change and global warming have prompted a reconsideration of previously used fuel energy sources to reduce greenhouse gas emissions. This has resulted in an emphasis on the usage of various biofuels. Among biofuels, pearl millet lignocellulosic feed stock with high cellulose (41.6%) and hemicellulose (22.32%) concentration is a significant source of biofuel production, which may contribute to an increase in farmer income (Packiam et al., 2018).

Value-added products are also gaining popularity, promoting the consumption of pearl millet. Pearl millet can be used for making various traditional food products (e.g., khichri, roti, sakarpare, gulgule, and ladoo), while industries in India are also using it for making products like noodles, pasta, vermicelli, biscuits, bread, cookies, cakes, and puffs. Several indigenous foods and drinks are also made from flour/meal and malt of the millet in Africa and are nutritionally superior to other cereals. Further, the millets market can be segmented based on type into pearl millet, finger millet, proso millet, foxtail millet, and others. In 2018, pearl millet held the greatest share in terms of product volume in the millets market and is likely to expand at >3% compound annual growth rate by 2025. The massive demand share of pearl millets is due to its rich nutritional value because it has eight times higher Fe content than rice (agriXchange, 2024). Millets contain high protein (up to 9.5 g/100 g for teff and fonio), ash, calcium (up to 344 mg/100 g for finger millet), P, and K (up to 250 mg/100 g), Fe, and Zn levels (Obilana & Manyasa, 2002). In West Africa, different countries have their unique food items made from pearl millet. The stiff or thick porridges (Tuwo or Tộ) are very famous and generally used in all the Sahelian countries, while Francophone countries like Senegal, Mali, Guinea, Burkina Faso, Niger, and Chad prefer steam-cooked couscous. The thin porridge "bouillie" is also popular in these countries. In Nigeria and Niger, the thin porridge "Fourra" and *Masa*, a fried cake, are quite popular, whereas "Soungouf" "Sankhal" and "Araw" are mainly popular in Senegal (Ajeigbe et al., 2020; Kaur et al., 2014). Its grains are also locally brewed to produce non-alcoholic or alcoholic beverages in Asia and Africa (Dwivedi et al., 2012) (Table 1.1).

Different Agro-ecologies for Pearl Millet Production in India

Pearl millet can grow in varying conditions from near-optimum with high external inputs to highly drought-prone environments. Prioritization of research in cognizance of production constraints and different requirements of various pearl millet–growing regions has led to the formation of three production zones (Zones A_1, A, and B) along with summer hybrids (Figure 1.1). Different public- and pricate-sector pearl millet breeding programs in India have their own product profiles, depending on the need of their target environment (Table 1.2).

Zone A_1 (Hyper-arid Zone)

Approximately 3.5–4.0 mha of pearl millet production lies under Zone A_1, which includes parts of Rajasthan, Gujarat, and Haryana, which receive <400 mm annual rainfall. Genotypes suitable for this area are early maturing (70 days), dual purpose, high yielding, high tillering, downy mildew, and blast resistant with

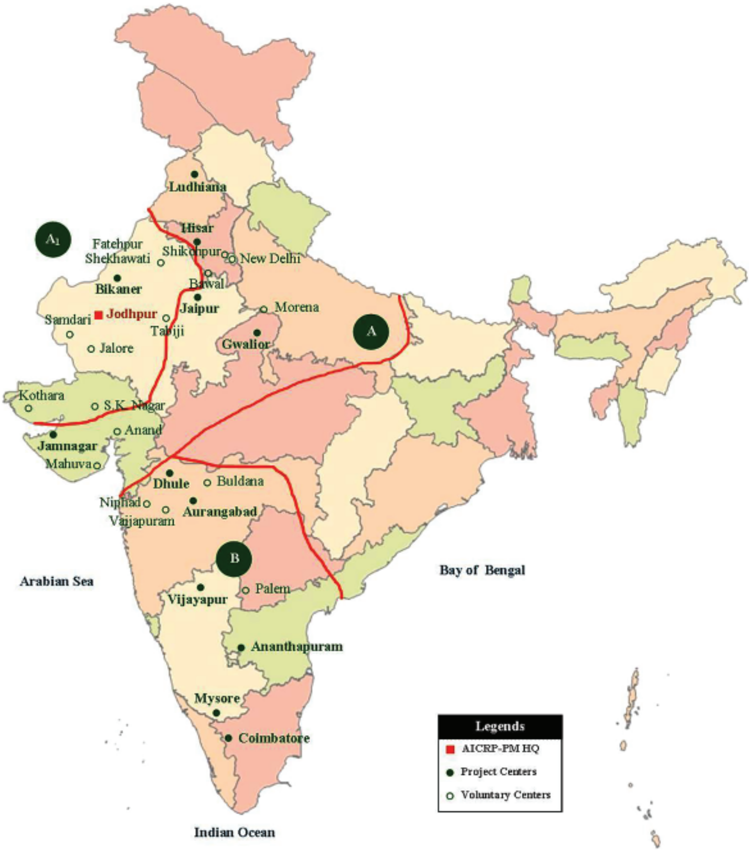

Figure 1.1 Geographical demarcation of Zones A_1, A, and B of pearl millet cultivation in India.

seedling stress tolerance. The seedlings contain benchmark levels of Fe (42 ppm) and Zn (32 ppm).

Zone A (Arid Zone)

Zone A comprises the remaining parts of the states of Rajasthan, Gujarat, and Haryana and the entire pearl millet growing areas of Uttar Pradesh, Madhya Pradesh, Punjab, and Delhi, covering 2.0–2.5 mha. This zone has sandy loam soils and annual rainfall >400 mm. Hybrids and populations suitable for this area are medium maturing (71–80 days), dual purpose, high yielding, downy mildew, and blast resistant with seedling stress tolerance. The seedlings contain benchmark levels of Fe (42 ppm) and Zn (32 ppm).

Table 1.2 Pearl Millet Product Profiles for Different Agro Ecologies of India.

	Zone A_1 (early duration)	**Zone A (medium duration)**	**Zone B (medium duration)**	**Summer**
Name of the commercial line to be replaced	HHB67 (improved)	MPMH 17	Pratap	Proagro 9444
Agro-ecologyzone	Aridzone (Zone A_1)	Zone A	Zone B (medium duration)	Summer pearl millet area
Year of release	2005	2012	2012	2004
Basic traits/unique selling features				
Basic trait 1	Early duration (<45 days)	Medium duration (48 days)	Medium duration (51 days)	Late duration (58 days)
Basic trait 2	Grain yield (~2.0 t/ha)	Grain yield (2.8 t/ha)	Grain yield (2.9 t/ha)	Grain yield (4.0 t/ha)
Basic trait 3	Stover yield (~3.7 t/ha)	–	Stover yield (6.2 t/ha)	Stover yield (7.7 t/ha)
Basic trait 4	Downy mildew (5%)	Downy mildew (5%)	Downy mildew (3.26%) <5%	Downy mildew (2.44%) <5%
Basic trait 5	Blast resistance (3 score)	Blast resistance (3 score)	Blast resistance (4.5 score)	Blast resistance (4.7 score)
Basic trait 6	Rust, smut, and ergot ≤20%	Rust, smut, and ergot ≤20%	Rust, smut, and ergot ≤20%	Rust, smut, and ergot ≤20%
Basic trait 7	Fe ≥42 ppm	Fe 41 ppm	Fe 49 ppm	Fe 48 ppm
Basic trait 8	Zn ≥32 ppm	Zn 34 ppm	Zn 45 ppm	Zn 36 ppm
Value-added trait 1	Grain yield	Grain yield	Grain yield	Grain yield
Future unique selling point	High yield under arid zone	High yield under semi-arid zone	High yield under B zone	High yield under summer cultivation
Trait compared with the benchmark	10% more grain yield	10% more grain yield	10% more grain yield	5% more grain yield
Value added trait 2	Better blast resistance	Better blast resistance	Blast resistance	Downy mildew and blast resistance
Advanced testing for government registration or private sector licensing	5 years	5 years	5 years	5 years

Zone B (Semi-arid Zone)

Zone B covers 1.0–1.5 mha from the states of Maharashtra, Karnataka, Tamil Nadu, and Andhra Pradesh with rainfall >600 mm, heavy soils, and mild temperatures. They are medium- to late-duration hybrids and populations maturing in >80 days or more and are high yielding and downy mildew and blast reistant. The seedlings contain benchmark levels of Fe (42 ppm) and Zn (32 ppm).

Summer Hybrids

The summer pearl millet growing region covers 0.4 mha area, comprising parts of Gujarat and Uttar Pradesh. Suitable genotypes include medium- to late-duration hybrids maturing in >80 days and are high yielding, dual purpose, and downy mildew and blast resistant. The seedlings contain benchmark levels of Fe (42 ppm) and Zn (32 ppm).

Trends in Global Pearl Millet Production

Pearl millet is a descendant of the wild West African grass and was domesticated over 4,000 years ago in the West African Sahel, spreading later to East Africa and India (Sharma et al., 2021). Millet cultivation has expanded globally to >30 million ha, with the largest portion grown in Africa (>18 million ha), followed by Asia (>10 million ha). This crop contributes to half of the world's millet production, with 60% of the cultivation area located in Africa and 35% in Asia (Raheem et al., 2021; Satyavathi et al., 2021). As per the fourth advance estimates during 2021–2022. the pearl millet area in India was 6.70 million ha, with an average production of 9.62 million tons and 1,436 kg/ha productivity (Directorate of Millets Development, 2024). Over 65 years, pearl millet productivity has increased fourfold (or 400%) from 305 kg/ha in 1951–1955 to 1,290 kg/ha in 2016–2020, and it was 1,436 kg/ha during 2021–2022. Large-scale adoption of high-yielding cultivars (of the >60% pearl millet area under hybrids and improved varieties, >90% is under hybrids) by Indian farmers is the main reason for the increase in its production and productivity. The Indian states of Rajasthan, Maharashtra, Uttar Pradesh, Gujarat, and Haryana are the primary producers of pearl millet, accounting for 90% of the total production in the country. Among all the states, Rajasthan contributes a maximum of around 3.75 million tons, followed by Uttar Pradesh (1.94), Haryana (1.12), Gujarat (1.05), Madhya Pradesh (0.86), and Maharashtra (0.47), during 2021–2022 (Directorate of Millets Development, 2024) (Table 1.3). The crop is primarily grown during the rainy season (*Kharif*) from June/July to September/October, although it is cultivated in certain regions of Gujarat, Rajasthan, and Uttar Pradesh during the summer season (February–May). In

Table 1.3 State-wise Area, Production, and Productivity of Pearl Millet in India.

	2020–2021			2021–2022		
State	**Area**	**Production**	**Yield**	**Area**	**Production**	**Yield**
	lakh ha	lakh tons	kg/ha	lakh ha	lakh tons	kg/ha
Andhra Pradesh	0.31	0.71	2,281	0.31	0.55	1,782
Bihar	0.04	0.05	1,134	0.03	0.03	1,134
Chhattisgarh	0.00	0.00	515	0.00	0.00	446
Gujarat	4.60	10.09	2,192	4.46	10.56	2,368
Haryana	5.69	13.50	2,372	4.83	11.20	2,318
Himachal Pradesh	0.01	0.00	557	0.01	0.00	557
Jammu and Kashmir	0.00	0.00	0	0.00	0.00	0
Jharkhand	0.00	0.00	643	0.00	0.00	618
Karnataka	2.22	2.76	1,241	1.47	1.71	1,161
Madhya Pradesh	3.27	7.38	2,256	3.43	8.69	2,533
Maharashtra	6.88	6.57	955	5.26	4.75	903
Odisha	0.01	0.01	622	0.02	0.01	615
Punjab	0.00	0.00	640	0.01	0.00	650
Rajasthan	43.48	45.61	1,049	37.36	37.51	1,004
Tamil Nadu	0.67	1.59	2,357	0.60	1.57	2,616
Telangana	0.10	0.09	930	0.04	0.03	823
Uttar Pradesh	9.07	20.14	2,221	9.04	19.49	2,156
West Bengal	0.00	0.00	425	0.00	0.00	428
Other	0.16	0.13	848	0.16	0.12	751
All India	76.52	108.63	1,420	67.03	96.24	1,436

Note: 2020–2021 APY data: Directorate of Economics and Statistics, GOI and 2021–2022 APY data, fourth advance estimates: Directorate of Millets development, Jaipur.

addition, it is grown on a smaller scale in Maharashtra and Gujarat during the post-rainy (*Rabi*) season from November to February.

Globally, millets are cultivated in 93 countries, and only seven countries (India, Niger, Sudan, Nigeria, Mali, Burkina Faso, and Chad) have >1 M ha harvested area, whereas around 25 countries have >0.1 M ha harvested area. All contribute around 97% of the total world millet harvested area (34.1 M ha). In general, >97%

of millets production and consumption is by developing nations. It has been estimated that from 1961 to 2018 around 25.71% of the area under millets cultivation has declined across the continents. However, global millet productivity has increased by 36% from 1961 (575 kg/ha) to 2018 (900 kg/ha) (Meena et al., 2021). 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, with 8.5 million ha cultivated and an average production of 9.4 million tons. Western and Central Africa (WCA) is the largest pearl millet–producing region in Africa and the world. Segregated data on the pearl millet area for WCA are 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 under pearl millet. Overall, the SENA region has ~3.0 m ha under pearl millet cultivation (Jukanti et al., 2016).

In Africa, the WCA region (Nigeria, Niger, Chad, Mali, and Senegal) and east/southern Africa, which includes Sudan, Ethiopia and Tanzania, are the two main areas of pearl millet cultivation. Pearl millet is the third major crop in sub-Saharan Africa, with Nigeria, Senegal, Chad, Mali, Niger, and Burkina Faso as the major producing countries. Pearl millet has socio-economic, food/feed, health, and environmental impacts on the resource-poor people of Africa. The WCA region produces the most pearl millet in the world, with 95% of the crop grown in the region (Jukanti et al., 2016). West Africa is the largest producer, led by Nigeria (41%), Niger (16%), Burkina Faso (7%), Mali (6.4%), Senegal, and Sudan (4.8%). Across Africa, millet is produced in 18.50 million ha by 28 different countries, with a yield of 11.36 million tons. It covers 30% of the SAT areas of the continent and is grown in diverse agro-ecologies. Because the region makes up 49% of the global millet area, it holds great significance (FAO, 2019). The area under millet production in different countries across the world is depicted in Figure 1.2.

According to recent report by the Agricultural and Processed Food Products Export Development Authority (APEDA, 2024), the global production of millets stood at 90.65 million tons in 2022. India was the highest millets–producing country in the year 2022, with production of 17.60 Mn million tons, contributing 19% of the global production. It was followed by Nigeria (9.00 Mn million tons; 10.01%), Sudan (6.50 Mn million tons; 7.23%), the United States (6.21 Mn million tons; 6.91%), and China (5.70 Mn million tons; 6.34%) (Table 1.4).

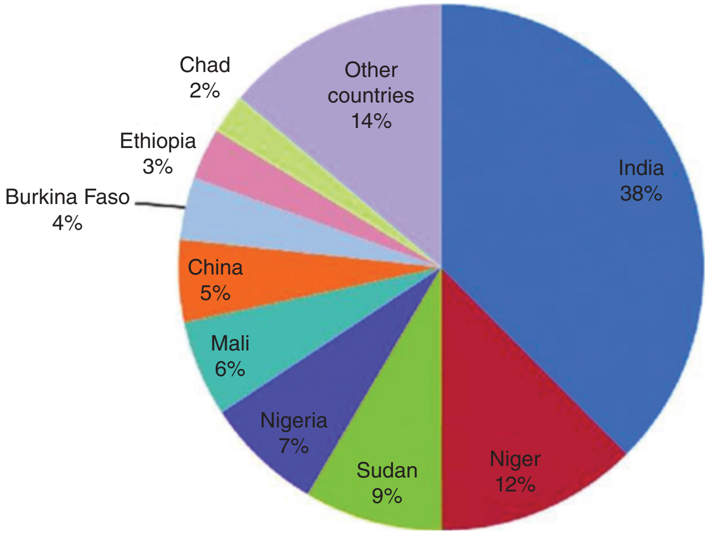

Figure 1.2 Millet production (%) in different countries of the world (FAO, 2018).

Table 1.4 Top Five Countries in Millets Production, 2022.

Rank	Country	Production 000MT	Share of global production %
1	India	17,600	19
2	Nigeria	9,000	10.01
3	Sudan	6,500	7.23
4	United States	6,212	6.91
5	China	5,700	6.34

Note: APEDA (2022).

Trends in Global Millet Consumption

The use of millet is primarily limited to developing nations, particularly following a significant decline in production and consumption within the Commonwealth of Independent States (CIS), which was previously the largest producer in the developed world. According to estimates, ~80% of millet produced worldwide (with a staggering 95% in Asia and Africa) is used for human consumption. The remaining proportion is divided among feed (7%) and other uses, such as seed and beer and waste. The per capita consumption of millet for food varies greatly between countries. It is most prevalent in Africa, where millet serves as a crucial food source in regions with low rainfall. In Niger, millet accounts for ~75% of all cereal food consumption, while in many other Sahelian countries it represents >30%. Additionally, it is a significant crop in Namibia, where it comprises 25% of total cereal food consumption, and Uganda, where it makes up 20%. Outside of Africa, millet is also an important food source in certain regions of India, China, and Myanmar. Millet is a highly nutritious and energizing food and is especially recommended for children, convalescents, and the elderly. Millet is used in various food preparations that vary across countries and regions. These typically include porridge or a flatbread that resembles a pancake. However, because whole meal quickly goes rancid, millet flour (prepared by pounding or milling) can be stored only for short periods.

Worldwide, millet food consumption has grown only marginally over the past 30 years, whereas total food use of all cereals has almost doubled. Millet is nutritionally equivalent or superior to other cereals. However, consumer demand has fallen because of several factors, including changing preferences in favor of wheat and rice, irregular supplies of millet, and cereal-centric government policies and promotions. Particularly in urban environments, the cost of women's time has encouraged the shift from millet to readily available processed foods (milled rice, wheat flour, etc.) that are faster and more convenient to prepare. 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. Preparations from processed pearl millet flour contain less 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) at 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 that 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 ratios (Sumathi et al., 2007). Popped pearl millet has better nutritional quality. Popped millet is a good source of energy, fiber, and carbohydrates and is used in producing supplementary or weaning foods for children. Malting helps in the production of easily digestible, high-calorie, and low-viscous weaning foods, which are essential during the transition of infants from breast feeding to other type of foods. Pearl millet's high fiber content and gluten-free nature coupled with its relatively good nutritional composition 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 (Jukanti et al., 2016). The utilization of millet grain as animal feed is not significant. It is estimated that <2 million tons (~7% of total utilization) is fed to animals, compared with about 30 million tons of sorghum (almost half of total output). Animal feed usage of millet grain is largely concentrated in developing countries in Asia , with limited usage in Africa. It is important to mention that the millet fodder and stover are valuable and critical resources in the crop/livestock systems. Based on calculations of feed use in the CIS, it is estimated that ~1.0 million tons per annum are currently used as animal feed in developed countries. Western Europe, North America, and Japan together use slightly over 200,000 tons, almost exclusively as bird seed. The current rise of pearl millet as a more affordable alternative to maize feed in aquaculture, dairy, and poultry farming in India and the southeastern United States is not thoroughly documented. Nonetheless, it only accounts for a minor portion of the overall feed grain usage at present.

Current Global Scenario of Millet Consumption

The global consumption of millets stood at 90.43 Mn MT in the year 2022. The top 10 countries contributed to nearly 80% of the total global millet consumption in the same period. Millets displayed their highest consumption in India with 17.75 Mn MT, followed by China (13.70 Mn MT) and Nigeria (8.80 Mn MT) (APEDA, 2022) (Figure 1.3).

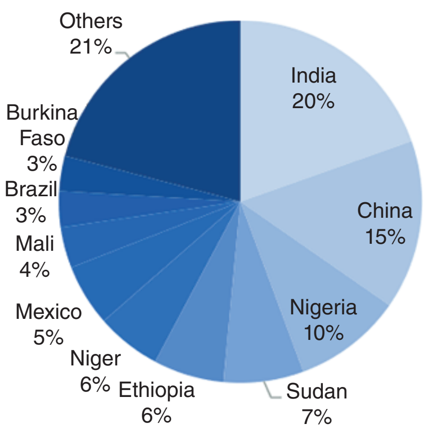

Figure 1.3 Global consumption of millets (APEDA, 2022).

International Trade Market for Pearl Millet

The limited market for pearl millet due to low consumer demand, including among farmers, is a cause for concern. Usually, this crop is being grown for food security instead of large-scale marketing, which is a major obstacle to its growth; hence, the market participation and price are quite low in comparison to other major cereals. The Minimum Support Price system could not be very helpful in this case because pearl millet is mostly sold in the local market and marketing of the produce is usually not in bulk. In addition, it has received inequitable treatment in terms of price in comparison to other major cereals (Deshpande & Rao, 2004). Poor post-harvest processing with no policy support; unorganized markets; the lack of an information system; excessive middlemen; meager transportation associations; inadequate bargaining capacity; lesser vertical coordination among producers, processors, and consumers; and poor processing facilities are some of the other major issues to be addressed to improve its trade and consumption. It is important to establish targeted policies that address the challenges faced by farmers. These individuals often encounter insufficient markets for their crops, particularly in comparison to major staples such as rice, wheat, and oilseeds, as well as pulses. Additionally, pearl millet is sold at a lower price compared with other cereals, causing producers to be economically challenged because they are only able to meet their production costs. The use of value addition strategies along with backward and forward linkages for the value chain is needed in domestic and international markets to gear up the consumption of this nutricereal.

However, millet exports over the past 5 years (2016–2021) show a positive trend in both value (3.10% CAGR) and volume (0.37% CAGR), indicating the recouping of the millet trade. In 2018, pearl millet held highest share in terms of product volume in the millets market and is likely to expand to >3% CAGR by 2025. The massive demand share of pearl millets is due to its rich nutritional value as it has eight times higher Fe content than rice (https://agriexchange.apeda.gov.in). Bajra (pearl millet) and Ragi (finger millet) together contributed 42.12% in terms of value (USD 27.42 Mn) and 54.41% in terms of volume (91,280 MT) in the year 2021 (Figure 1.4).

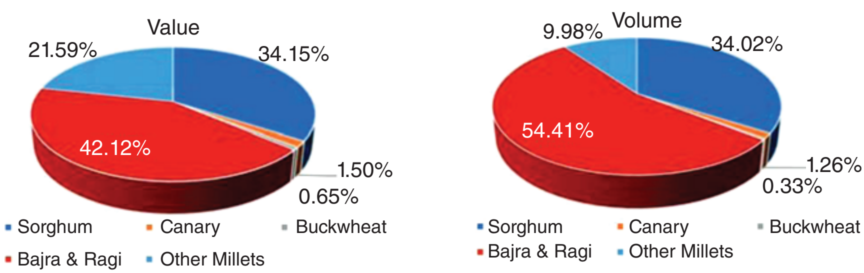

Figure 1.4 Category-wise share of millets in India's export in terms of value and volume (2021) (APEDA, 2022).

Challenges and Opportunities for Enhancing Pearl Millet Production

Pearl millet production has declined in the past several years mainly due to changing consumer preferences and pro-cereal government policies. Its production usually fluctuates widely from year to year due to rainfall variability and drought in the major production areas. In addition, several other factors, such as cultivation on poor soils, use of limited inputs, obsolete farming techniques, inadequate research resources, lack of industrial usage, and non-availability of value-added technologies, are also responsible for this decline. The hybrids and varieties developed so far are mainly for well-endowed production ecologies, whereas most of the breeding programs are not targeted to develop products for arid and hyper-arid ecologies, which is the area of utmost priority. Hence, there is a dire need to give priority to generate breeding programs and augmenting cultivar diversity for the arid and hyper-arid ecologies. It is worth concentrating on developing OPVs specifically for arid regions because it is challenging to produce sustainable hybrids with high yields for this area. It can reduce seed cost, which in turn can lead farmers to retain seed for generations, ultimately reducing the cost of cultivation. Sustainable breeding components (e.g., advanced genomic tools, speed breeding, and pre-breeding) and management components (e.g., natural resource management, better water conservation techniques, high soil fertility, and good production practices) are some of the ways to improve pearl millet productivity (Twomlow et al., 2008). Pearl millet has high nutritional value, which can be exploited for improving nutritional quality and combating malnutrition. Hence, the development of food and value-added products from pearl millet should be focused to make it more acceptable as an alternative crop of the future.

A variety of socio-economic constrictions has also limited the production and consumption of pearl millet, leading to a loss in cultivated diversity. Rural people of western Rajasthan usually prefer local landraces or “Bajri” for consumption. Thus, more efforts should be put into their development and use in the breeding programs. Landraces should be used to develop donor lines and create locally adopted base populations that can be further used as mother stocks to develop target lines in breeding programs of arid ecology. Subsequently, mechanized harvesting and the development of pearl millet hybrids/varieties with high regeneration capability and tolerance to salt and high temperature are among some of the issues which should be focused on for its improvement. Rancidity is another big challenge in pearl millet. Although pearl millet possesses superior nutritional qualities, the poor shelf life of the flour is the main challenge towards promotion and utilization of products from pearl millet. Hence, a major focus should be put on enhancing the shelf life of pearl millet flour. Varieties with reduced phenolic compounds and fat content that can have longer shelf life should be developed to overcome this issue. There is also a need to investigate its nutraceutical value and the associated health benefits for developing new industries. Difficulty in processing is another social issue that needs attention because pearl millet is generally processed at a household level in rural areas. Millet is conventionally pounded in a mortar, but mechanical dehulling and milling are increasingly used because they can eliminate a considerable amount of hard labor and can improve flour quality.

Conclusion

Pearl millet is a climate-resilient crop and an excellent genomic resource for candidate genes responsible for tolerance to climatic and edaphic stresses. It can be exploited for the genetic improvement of other crops. Pearl millet has the potential to become a significant food and feed crop due to its superior tolerance to drought, high temperature, and salinity compared with other cereals. This makes it an excellent alternative for ensuring nutritional security. Extensive collection and characterization of pearl millet germplasm are important for developing a strong breeding program and developing superior varieties. The continuous downfall in the global area under millets may be attributed due to the area shifting to other crops, changing food habits, assured irrigation facilities, and ensured returns from major commercial crops. Thus, it is important to redirect breeding efforts toward identifying specific end-product traits rather than solely focusing on improving productivity to fully unlock the potential of this crop. Further, collaborative efforts of breeders, physiologists, agronomists, policymakers, and donors in both individual and institutional capacities are highly needed. To combat abiotic stresses and develop tolerant varieties, it is important to have specific phenotyping platforms to assess tolerance to high temperatures and drought. To target key traits and speed up cultivar development, modern breeding tools and platforms, along with genomic designing and approaches, are necessary. Specific policies need to be developed to address the issues of farmers because the pearl millet farmers face relatively imperfect markets compared with superior cereals, pulses, and oilseeds. Moreover, the low prices received will make them economically inefficient, merely meeting the production costs. Providing backward and forward linkages for the value chain using innovative value addition in domestic and international markets is also highly needed. Considering its nutraceutical properties, the capacity for social capital formation among farmers and consumers regarding cooperation for millet cultivation and consumption is also essential. Thus, private–public partnership and investment is necessary to breed varieties with high starch content, targeting 100% substitution of pearl millet with maize, rice, etc. in alternative uses. In order to enhance demand and consumption from consumers, there is a need to establish a link between the health and consumption of traditional food grains and to invite initiatives from different stakeholders.

Pearl millet has superior nutritional qualities, but the shelf life of its flour and bioavailability are major challenges in the promotion of pearl millet products. Thus, efforts should focus on enhancement of shelf life of pearl millet flour, biofortification for Fe and Zn, and generating authentic data on the nutritional benefits and bioavailability of pearl millet. Varieties must be developed that possess the capacity to enhance the shelf life of flour and reduce the undesirable attributes in the grain (e.g., reducing fat content and phenol compounds), followed by exploring the health benefits and nutriceutical value for pearl millet. Providing backward and forward linkages for the value chain using innovative value addition in domestic and international markets is also needed. High-throughput genome analysis, next-generation sequencing techniques, and genome editing can aid in trait discovery, mapping, and line improvement. Discovering sequence-based molecular markers associated with important agronomic traits will enhance opportunities for pearl millet improvement and cultivar development in the future. There is a great potential for harnessing its 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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