Improving Millets

Improving Millets:

The Underutilized High-Value Crops

By

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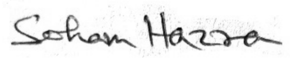
PREFACE

In recent years, there has been a growing recognition of the importance of sustainable agriculture, nutritional security, and climate resilience in global food systems. Millets, often overshadowed by major cereals like rice, wheat, and maize, are emerging as crucial players in this narrative. As climate change continues to challenge agricultural productivity and food security, millets, with their inherent resilience and nutritional benefits, present a promising alternative.

This book, "**Improving Millets: The underutilized high value crops**" aims to provide a comprehensive and up-to-date account of the breeding techniques, genetic advancements, and cultivation practices specific to a wide range of millets like pearl millet, foxtail millet, finger millet, proso millet, kodo millet and barnyard millet. It is designed to serve as a valuable resource for researchers, agronomists, students, and policy makers who are committed to enhancing the productivity and resilience of this vital group of crops. Millets have been cultivated for thousands of years, primarily in the semi-arid regions of Africa and Asia. Despite their historical significance and adaptability, millets have often been neglected in modern agricultural research and development. However, the tide is turning as the global community recognizes the need for crops that can withstand harsh environmental conditions while providing superior nutritional benefits. Rich in essential amino acids, vitamins, and minerals, millets are not just crops for the poor but are superfoods that hold the potential to address malnutrition and health issues across diverse populations.

In this book, we delve into the biology and genetics of various millet species, including pearl millet, finger millet, foxtail millet, proso millet, and barnyard millet. We explore the traditional and modern breeding techniques that have been employed to enhance their yield, disease resistance, and nutritional quality. Our coverage spans from classical breeding methods to cutting-edge genomic approaches, providing a holistic view of the advancements in millet breeding. In the last chapter, sorghum was also added with the intention of providing readers with a wholesome of satisfaction.

It is our hope that this book will inspire and equip a new generation of researchers and practitioners with the knowledge and tools needed to advance the breeding and cultivation of millets. By embracing these resilient crops, we can build a more sustainable, nutritious, and secure food future.



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FOREWORD

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In an era where global food security is of paramount concern, the importance of diversifying our agricultural practices cannot be overstated. 'Improving Millets: The Underutilized High Value Crops' is a timely and essential contribution to the discourse on sustainable agriculture and nutrition. Millets, often overshadowed by more widely cultivated grains, hold remarkable potential for addressing food security challenges due to their resilience, nutritional value, and adaptability to diverse climates.

This book brings together the latest research and insights on enhancing the productivity and utilization of millets. The authors have meticulously documented the book that can serve as a roadmap for researchers, farmers, policymakers, and industry stakeholders.

As we confront the pressing issues of climate change, resource scarcity, and malnutrition, 'Improving Millets' underscores the urgency of rethinking our approach to agriculture. It invites readers to recognize the untapped potential of millets and to join a global movement towards a more resilient and nutritious food system. The knowledge encapsulated in this book is not just academic; it is a call to action to embrace and promote these invaluable crops for a sustainable future.

Prof. (Dr.) Manik Gopal Som

1. INTRODUCTION

Food and Agricultural Organization and United Nations has recognised the year 2023 as the International Year of Millets. Millets are a diverse group of small-seeded grasses that have been cultivated for thousands of years. These grains are highly nutritious and have played a significant role in the diets of various cultures around the world. Millets are known for their resilience and ability to thrive in harsh environments with minimal water and soil requirements, making them an excellent choice for sustainable agriculture. Millets encompass a wide range of species, including pearl millet, foxtail millet, finger millet, proso millet, kodo millet, barnyard millet, kakun millet and others.

Millets were among the initial crops to be domesticated by humans in Asia and Africa, and they subsequently became essential food sources globally. They are generally short duration crops (60-120 days), hence get fit to a wide range of cropping systems. Millets are generally *kharif* season (sown during May-June) crops. However, they also grow well during *rabi* season (sown during October-November) and summer season (sown during January-February). Millets are considered as drought tolerant crops since they require less water than conventional cereal crops *viz.,* rice, wheat. Each variety has its own unique characteristics, but they share some common traits that make them stand out from other grains. Millets are naturally gluten-free, rich in dietary fibre and packed with essential nutrients like iron, magnesium, phosphorus, and B-vitamins. These grains also have a low glycemic index, making them suitable for individuals with diabetes or those aiming to maintain stable blood sugar levels.

The cultivation of millets dates back to ancient times, with evidence of their consumption found in archaeological sites across Africa, Asia, and Europe. They have been staple foods in regions like Africa's Sahel belt, India, and parts of China for centuries, contributing to the food security and resilience of these communities. During the course of time the importance of millets reduced due to the large-scale cultivation of rice, wheat and other major cereals. However, in the recent years, millets have gained renewed attention due to their nutritional value, environmental sustainability, and potential to address global food challenges, such as malnutrition, climate change, and water scarcity.

Millets are incredibly versatile and can be used in a variety of culinary applications. They can be milled into flour for making bread, rotis, and pastries, or cooked whole as a base for pilafs, porridges, and salads. Additionally, millets can be popped like popcorn, turned into flakes for breakfast cereals, or used in brewing alcoholic beverages. The wide range of millet-based products offers a diverse and healthy alternative to traditional cereal grains by reducing the risk of the lifestyle diseases *viz.,* diabetes, hypertension, cardio vascular disease, etc (Amadou et al. 2013). Millets express high levels of Tryptophan which produces serotonin required to calm the mood. Millets also help to reduce cholesterol, triglycerides and C-reactive protein by virtue of the presence of Niacin. Millets are also high in fibre content, hence prevents us from being constipated.

As we strive to promote sustainable agriculture, improve nutrition, and mitigate the impact of climate change, the resurgence of millets presents a promising solution. Their nutritional benefits, adaptability to different growing conditions, and ability to support small-scale farmers make them important crops for both food security and environmental conservation. By embracing the diversity and resilience of millets, we can pave the way for a more sustainable and nourished future.

1.2. Millets: The Powerhouse of Nutrition

Millets offer nutritional security and there is a need for promoting millets as they are abundant in nutrients and health-beneficial compounds, making it suitable as food and feed. Millets serve as excellent energy sources, offering a range of essential nutrients *viz.,* protein, fatty acids, minerals, vitamins, dietary fiber and polyphenols. Typically, millet protein is abundant in essential amino acids, particularly those containing sulfur *viz.,* methionine and cysteine. The processing of millet through milling results in the removal of the bran and germ layers, which are rich in fiber and phytochemicals, leading to a notable loss. Millets serve as a source of antioxidants, including phenolic acids and glycated flavonoids. Finger millet tops in anti-oxidant activity among the common Indian foods. Millet-based foods exhibit characteristics that make them potential prebiotics, capable of enhancing the viability or functionality of probiotics, thereby offering significant health benefits. The comparative nutrient profile of cereals and millets are presented in Table 1.1. Similar to the cereals, millets possess a substantial amount of carbohydrate energy and nutritional value, rendering them valuable in maintaining a balanced diet.

Table 1.1. Nutritional value of millets (Per 100 g)

Grain/Nutrient	Pearl-millet	Finger Millet	Fox-tail millet	Proso millet	Barnyard millet	Kodo millet	Rice	Wheat	Maize
Energy (Kcal)	361	328	331	341	397	309	345	346	342
Protein (g)	11.6	7.3	12.3	7.7	6.2	8.3	6.8	12.1	11.1
Fat (g)	5.0	1.3	4.3	4.7	2.2	1.4	0.4	1.7	3.6
Calcium (mg)	42.0	34.4	31.0	17.0	20.0	27.0	10.0	48.0	10.0
Iron (mg)	8.0	3.9	2.8	9.3	5.0	0.5	3.2	4.9	2.3
Zinc (mg)	3.1	2.3	2.4	3.7	3.0	0.7	1.4	2.8	2.2
Thiamine (mg)	0.33	0.42	0.59	0.21	0.33	0.33	0.06	0.49	0.42
Riboflavin (mg)	0.25	0.19	0.11	0.01	0.10	0.09	0.06	0.10	0.17
Folic acid (mg)	45.5	18.3	15.0	9.0	-	23.1	8.0	20	36.6
Fibre (g)	1.2	3.6	8.0	7.6	9.8	9.0	0.2	2.7	1.2

Integrating millets with alternative protein sources can address the deficiency of specific amino acids like lysine. Given the nutritional significance of millets, it is imperative to examine the nutritional characteristics and functional properties of various millet cultivars, as well as to develop value-added products derived from millets. Successful improvement of these characteristics is essential for broadening the range of uses for millet grains.

1.3. Current status of millets

Millets are cultivated in 93 countries globally, but only 7 of these countries have more than 1 million hectares dedicated to millet cultivation. Generally, over 97% of millet production and consumption occurs in developing nations. Between 1961 and 2018, the area dedicated to millet cultivation worldwide decreased by approximately 25.71%. Despite this, global millet productivity has increased by 36%, rising from 575 kg/ha in 1961 to 900 kg/ha in 2018. Data from the past 58 years show that millet production has declined in most regions, except for Africa, where West Africa saw the highest increase, nearly doubling since the 1960s. In Asia, although the area for millet cultivation decreased, production gradually increased, enhancing productivity. In India, millet production peaked in the 1980s but then gradually declined due to a significant reduction in the cultivated area. India remains the largest millet producer, contributing 37.5% of the global output, followed by Sudan and Nigeria. The highest global millet import and export values were recorded between 2011 and 2017, at 155.26 million and 127.60 million USD, respectively. The global decline in millet cultivation area is attributed to the shift towards other crops, changes in dietary habits, better irrigation facilities, and the reliable returns from major commercial crops. Due to their unique nutritional profile, significant health benefits, and C_4 photosynthetic pathway, millets are ideal for diversifying cropping systems and promoting climate-resilient agriculture. Historically, resource-poor farmers in drylands and tribal communities in less productive and fragile ecosystems have cultivated millets. However, increased awareness of their health benefits and industrial uses has led to a resurgence in millet cultivation. A major concern is the shrinking global millet cropping area. The lack of improved cultivars, agricultural inputs, and policy support are key factors limiting millet productivity and cultivation area. To promote millets as valuable crops of the future, well-planned, long-term public sector investment in multidisciplinary research by major millet-growing countries is necessary. For example, in India, the government has introduced the Initiative for Nutritional Security through Intensive Millet Promotion

(INSIMP). Recognizing the immense nutraceutical potential and climate resilience of millets, the Indian government has launched a national nutraceutical mission. This comprehensive national strategy has prioritized millets *viz.,* pearl millet, finger millet, barnyard millet, foxtail millet, proso millet, kodo millet, and little millet and two pseudocereals *viz.,* amaranth and buckwheat designating them as nutri-cereals. To boost indigenous millet production, the government declared 2018 as the National Year of Millets. Additionally, the UN Food and Agriculture Organization (FAO) declared 2023 as the International Year of Millets. Similar national and international public sector initiatives are needed from other major millet-growing countries to promote millets and increase their consumption. Linking millets to industry through value addition can provide higher returns to marginal farmers in Asia and Africa. Overall, policy support, focused crop improvement efforts, and public awareness of their nutritional benefits will help restore the lost millet cultivation area.

1.4. International Trade

Majority of the millet grains are consumed where they are produced since they 97% of the total cultivation are grown particularly by resource-poor and marginal farmers. However, from the 1960s to 2017, millet imports and exports increased by 25.4% and 25.9%, respectively. Over the past decade, millet imports and exports reached 374.5 thousand tons and 376.4 thousand tons, respectively (Table 1.2). A significant rise in imports occurred in the 1970s, primarily due to increased demand in Europe. The global value of millet imports and exports also rose, peaking at $155.26 million and $127.60 million, respectively, between 2011 and 2017. Data from 2010-2017 shows that Asia is the largest importer of millet, accounting for over 65% of global imports, while the Americas are the largest exporter, representing over 83% of global millet exports. India, the United States, Argentina, and China together contribute over 33% of millet exports (FAOSTAT 2018), with India leading in pearl millet exports, the United States in proso millet, and China in foxtail millet.

Table 1.2. Millet grain productivity (kg/ha)

Year	1961–1963	1971–1973	1981–1983	1991–1993	2001–2003	2011–2013	2016–2018
Africa	586	559	714	649	720	597	677
Eastern Africa	707	766	987	904	900	1061	1170
Middle Africa	642	586	605	494	580	522	586
Northern Africa	641	360	301	262	260	319	525
Southern Africa	339	281	305	265	249	201	221
Western Africa	558	547	750	674	804	602	673
Americas	1223	1176	1247	1486	1269	1361	2166
Northern America	1192	1297	1356	1448	1214	1326	2177
Central America	0	0	0	1030	909	1000	5595
Caribbean	0	0	0	0	0	0	0
South America	1236	1087	1184	1595	1838	1763	1576

Asia	562	666	777	811	938	1171	1276
Central Asia	0	0	0	523	760	1025	1104
Eastern Asia	889	1195	1644	1846	1786	2219	2308
Southern Asia	433	489	584	686	864	1104	1210
South-eastern Asia	322	254	801	673	712	985	1025
Western Asia	1013	1180	858	601	682	732	689
Europe	583	982	761	765	1079	1301	1517
Eastern Europe	578	979	759	764	1057	1249	1424
Northern Europe	0	0	0	0	0	0	0
Southern Europe	1257	1551	1792	2252	2212	1727	1869
Western Europe	1293	2372	3129	0	3050	3400	3909
Oceania	1087	1067	975	855	814	1015	1022
Australia and New Zealand	1087	1067	975	855	814	1015	1022

1.5. Production Constraints

In many of the developing countries where millets are majorly grown, the markets for millet grains are underdeveloped, leading to poor economic returns for farmers. Additionally, the seed supply in most developing countries relies on informal seed chains, resulting in a lack of access to improved seeds and the widespread cultivation of less productive, heterogeneous landraces or local varieties (Rakshit and Wang 2016). There is dearth of better accessibility to inputs including improved varieties. Many minor millets are not adapted to modern agroecosystems and mechanization. This is mainly because of some inherent problems like high seed shattering and unsynchronized maturity. Besides these basic traits, grain size is also an important yield component as the very small seeds of millets are causing difficulties for mechanical planting and harvest and ultimately for their commercialization. Seeds of minor millets are subjected to dehulling before human consumption. The traditional methods of dehulling followed in developing countries are labour intensive and time-consuming (Sood et al. 2015). The drudgery involved in manual processing is an important factor in reduced consumption and commercialization of millets at a large scale. Climatic factors such as rainfall pattern and distribution, edaphic factors such as soil type, soil fertility, agronomic management, and moreover socioeconomic status of farming communities are equally important for better performance of millet production system (Sood et al. 2019). Incidence of diseases, insect-pests, parasitic nematodes, birds, parasitic plants, and weeds are the most important biotic constraints associated with millets. The important diseases of millets are downy mildew (pearl millet), blast (finger millet), smut (foxtail millet, barnyard millet), rust (foxtail millet) and ergot (pearl millet) (Strange and Scott 2005; Das 2013). Weed infestation is also considered as a major constraint in the global millet production as more than 29% reduction in millet grain yield is associated with weed infestation only (Burkill 1985). Striga, a semi-root parasitic weed is one of the major constraints for millet production in Africa causing huge yield losses in millets. Yield reduction due to striga is higher in sorghum and pearl millet than other crops (Ejeta 2007). Bird damage is also considered as a major biotic threat for millet growers, yield reduction may reach 100% in isolated crop fields (Sood et al. 2015). The manual weed management in the absence of robust preemergence weedicide coupled with manual bird scaring increases cost of quality seed production in minor millets. Abiotic constraints of millet production are mainly associated with environmental and soil factors such as moisture stress, nutrient stress, salinity, alkalinity, acidity, and heat stress. Among all, moisture stress is considered the most important constraint for millet production, as millets are mostly grown by resource poor farmers in drylands. Drought may occur at any physiological growth stage of millets. In African countries, drought is considered as one of the most important stresses for millet production (Matanyaire 1996; Gebretsadik et al. 2014). In India, millets are cultivated in two seasons, in the rainy and post rainy season. The low productivity of post rainy season is mainly associated with terminal drought stress (Patil 2007). As millets are grown on marginal land having low soil fertility and low organic carbon, salinity, and alkalinity that leads to low productivity of millets. Soil salinity and poor drainage severely affect the crop during the seedling emergence stage (Macharia et al. 1994). Changing food habits and consumer preferences have led to the shifting of land for the cultivation of other high-value cereal grains thereby lowering the production of millets. For instance, in India, the millet cropping area is reduced to 2.3 M ha during 2011–2012 compared to 8 M ha during the late 1940s, this reduction was mainly associated with shifting of millet cultivated area to other cereals grains (Seetharam 2015).

1.6. Research gap

a. Extension Gap

The difference between the yield achieved in demonstrations and the yield produced by farmers is referred to as the extension gap. Larger extension gaps indicate the extent to which modern technologies are being adopted. For Kharif Jowar, the yield gap was 10.90, 9.15, and 4.93 q/ha in the North Eastern Plain Zone, Eastern Plain Zone, and Vindhyan Zone of Uttar Pradesh, respectively. Over five years, the average extension yield gap for finger millet ranged from 4.82 to 5.29 q/ha, while for barnyard millet, it varied from 5.60 to 8.25 q/ha. In contrast, fodder yield demonstrated an even larger extension yield gap. Research indicates that the yield gap is primarily due to farmers not adopting the recommended practices. This is a major cause of the extension gap, highlighting the potential to improve yields among regional farmers.

b. Technological gap

The difference between the potential yield and the demonstrated yield is referred to as the technological gap. Over five years, the average technological gap for grain yield in finger millet ranged from 5.63 to 7.81 q/ha, and for barnyard millet, it ranged from 6.63 to 8.81 q/ha (Rawat et al. 2019). For fodder yield, the gap varied from 32.65 to 35.21 q/ha for barnyard millet and 27.65 to 30.21 q/ha for finger millet. The average technological gap for finger millet was 9.91 q/ha. The technological gap was measured over several years, with the smallest gap (1.81 q/ha) in 2017–18 and the largest (2.73 q/ha) in 2018–19, averaging 2.45 q/ha (Yadav et al. 2023). The average technological gaps for improved technology were 9.91 q/ha for finger millet, 5.43 q/ha for kodo millet, and 4.15 q/ha for tiny millet (Thakur et al. 2017).

Farmers face numerous challenges when growing crops, often hindering the adoption of improved agricultural methods recommended by research institutions. The challenges include lack of credit availability, inadequate irrigation facilities, labour management difficulties, limited availability of improved varieties, high fertilizer costs, irregular power supply, insufficient labour at critical times, and unavailability of biofertilizers. Rawat et al. (2019) reported the major problems faced by farmers include wild animal damage (86.67%), causing significant crop losses, followed by a lack of high-yielding varieties (81.17%), timely availability of quality seeds (78.33%), marketing issues (76.33%), lack of technical knowledge (74.78%), and the use of higher seed rates (71.50%). Additionally, diseases such as grain smut in barnyard millet and *Cercospora* leaf spot in finger millet were identified as significant constraints to grain production (41.67%), along with insect problems (21.17%).

1.7. Genetic resources

Diversity in crop cultivars is vital for sustainable agriculture, as germplasm provides the necessary variability for crop improvement. A narrow genetic base in cultivars increases the risk of crop failure due to pests, diseases, or climate changes. Worldwide, about 133,849 small millet germplasm samples are preserved in genebanks, along with 30,627 accessions of other related species (Table 1.3). Most of these accessions are stored in Asia (64.4%), followed by Africa (13.8%) and Europe (13.5%). These figures may vary due to duplicates within and between genebanks. Major collections of foxtail millet germplasm are found in China, India, France, and Japan. Abundance of finger millet is in India and African countries like Kenya, Ethiopia, Uganda, and Zambia, Proso millet in Russia, China, Ukraine, and India, Barnyard millet in Japan and India and Kodo millet in India and the USA. The largest collections by specific institutes include finger millet (9,522), kodo millet (2,180), and little millet (1,253) at the National Bureau of Plant Genetic Resources (NBPGR, India) followed by foxtail millet at the Institute of Crop Science, Chinese Academy of Agricultural

Table 1.3. Global status of cultivated, wild and weedy relatives of small millets germplasm conserved in genebanks

S. no	Crop name	Africa	Asia	United States of Americas	Europe	Oceania	Total
1	Finger millet (Elusine *coracana*)	6700	28,663	1456	36	18	36,873
	Other species of the genus *Elusine*	1628	256	20	40	22	1966
2	Foxtail millet (*Setaria italica*)	166	38,572	1145	4548	330	44,761
	Other species of the genus *Setaria*	976	209	341	372	9	1907
3	Barnyard millet (*Echinochloa colona* & *E.crus-galli)*	59	7444	316	53	51	7923
	Other species of the genus Echinochloa	248	371	71	8	9	707

4	Proso millet (*Panicum miliaceum*)	11	12,110	1147	15,812	228	29,308
5	Little millet (*Panicum sumatrense*)	7	2830	226	–	1	3064
	Other species of the genus *Panicum*	3853	9599	2161	677	142	16,432
6	Kodo millet (*Paspalum scrobiculatum*)	356	4043	354	14	13	4780
	Other species of the genus *Paspalum*	357	190	2812	41	524	3924

Sciences (ICS-CAAS) (26,233), barnyard millet at the Department of Genetic Resources I, National Institute of Agrobiological Sciences, Japan (3,671) and proso millet at N.I. Vavilov All-Russian Scientific Research Institute of Plant Industry (VIR) (8,778). Guinea millet accessions are found only at Centro Internacional de Agricultura Tropical (CIAT), Colombia (2) and the International Livestock Research Institute (ILRI), Ethiopia (1), with 2,087 accessions of the genus *Brachiaria* conserved globally. Except for finger millet, foxtail millet, and proso millet, the global conservation of germplasm of other crops is very limited. This scarcity is due to low research priority and the loss of landraces as traditional crops are replaced by cash crops and improved varieties. Therefore, collecting and conserving the existing diversity of millets is crucial before they are lost forever.

1.8. Breeding strategies for Millet improvement

Yield and its contributing factors are the primary focus in improving millets. Thus, selecting for yield has been the main strategy to enhance productivity. However, genotype × environment interactions significantly impact these traits. Consequently, assessing yield stability across various environments and examining physiological traits like harvest index and water use efficiency is crucial for increasing yield. Germplasm collections show significant variation in traits, including maturity duration, which can be leveraged to breed varieties tailored to different maturity groups (early, mid-late, and late) based on location-specific conditions such as soil, rainfall, temperature, humidity, day-length, and cropping patterns. Short-duration varieties suit double/intensive cropping regions, while medium to long-duration varieties are better for single cropping season areas.

Millets have high nutritional potential, but their use is limited by antinutrients like phytate, phenols, tannins, and enzyme inhibitors, which affect grain digestibility. Despite this, millets generally contain higher nutrient levels than major cereals, although there is considerable variability in germplasm for grain nutrients and antinutrients. Utilizing existing variability and hybridization-derived variations can aid in breeding nutrient-dense, high-yielding cultivars. Millets are well adapted to diverse climates and less affected by major biotic and abiotic stresses. However, diseases and pests still cause significant yield losses, making it essential to breed disease- and pest-resistant cultivars. For instance, blast disease in finger millet can cause yield losses of up to 88%, and other millets suffer from diseases like rust, smut, and leaf spots, and pests like shoot flies and stem borers.

Millets, mainly grown as rainfed crops, are highly susceptible to drought due to monsoon failure. Besides drought, lodging is a major problem due to soft stalks, crop management, and environmental factors. While there is no direct estimate of yield loss from lodging in millets, similar cereals like rice and wheat can lose up to 50% of their yield. Lodging happens when plants bend at maturity due to heavy panicles, soft stalks, and weak roots. As lodging is genotype-dependent and environmentally influenced, developing lodging-resistant cultivars is essential to minimize yield and quality losses. Another critical trait is shattering; significant yield losses occur due to grain shattering in millets, so shattering-resistant/tolerant varieties are necessary to prevent these losses.

Other important breeding goals for millets include developing machine-harvestable cultivars, enhancing grain and fodder nutritive value for higher market value, creating varieties suitable for value-added products (such as rice, flour, vermicelli, flakes, snacks, noodles, and ready-to-cook mixtures), and breeding shade-tolerant genotypes for orchards and agroforestry, quick-growing genotypes for intercropping, and genotypes suitable for rice-fallows. Targeted traits for millets improvement are discussed in Table 1.4.

Table 1.4. Targeted traits for improvement of millets for increased yield, adaptation and quality

Crop	Trait focus
Finger millet	Blast resistance, drought and salinity tolerance, machine harvestable, non-lodging, and bold grain size
Foxtail millet	Blast and sheath blight resistance, non-lodging, bold grain size, and strong culm for mechanical harvesting
Proso millet	Shoot fly and smut resistance, non-shattering, and non-lodging
Little millet	Shoot fly resistance, non-lodging, and bold grain size
Kodo millet	Shoot fly, head smut and sheath blight resistance, non-lodging, nutrient-response and drought recovery
Barnyard millet	Grain smut, sheath blight and shoot fly resistance, bold grain size, and non-shattering

1.9. Conventional Breeding approach

Various breeding methods such as pure line selection, pedigree selection, mass selection, and mutation breeding, typically used for self-pollinating crops, are also applied to millets. Historically, most small millet cultivars have been developed from selections of local landraces/cultivars, with a significant number also resulting from pedigree selection (hybridization and selection). For instance, in India, out of 248 small millet varieties (121 finger millet, 32 foxtail millet, 24 proso millet, 33 kodo millet, 18 barnyard millet, and 20 little millet), about 65% were developed from landrace selections, approximately 30% through pedigree selection, and 5% via mutation breeding. Similarly, in the USA, 11 proso millet cultivars were derived from landrace selections, while 8 were developed through pedigree selection.

Hybridization, followed by selection in segregating populations, has been a crucial breeding method, especially for finger millet, foxtail millet, and proso millet. In India, 45% of finger millet, 22% of foxtail millet, and 29% of proso millet cultivars were released using this method. However, hybridization in millets is challenging due to their floral morphology and anthesis behaviour. Techniques such as the contact method (enclosing panicles in a parchment bag to promote natural cross-pollination) and controlled hybridization (hand emasculation or hot water emasculation) are used. For instance, hot water treatment of inflorescence at 52°C for 5 minutes induces male sterility in finger millet, while 48°C for 4-5 minutes is effective for barnyard millet. Despite these techniques, the success rate of hybridization remains low, limiting genetic studies and yield improvements in millets.

Exploiting hybrid vigour in millets is limited due to hybridization difficulties. Developing male sterile lines is a viable alternative for using heterosis, a method successfully implemented in major crops for commercial hybrid seed production. So far, only one male sterile line has been reported in finger millet (INFM 95001), developed through chemical mutation (EMS). In China, several male sterile lines have been developed in foxtail millet, with partial genetic male sterile lines being used successfully in hybrid seed production. No male-sterile lines have been reported in other millets.

Mutation breeding has played a significant role in self-pollinated crops where hybridization is challenging. In India, mutation breeding has resulted in the release of 13 millet cultivars (8 finger millet, 3 kodo millet, and 2 little millet). The use of chemical hybridizing agents (CHAs) to induce male sterility in millets needs further exploration. The effectiveness of a mutagen depends on its mutagenic efficiency and effectiveness in inducing desirable mutations while minimizing undesirable changes. In finger millet, treatments with 500-600 Gray (Gy) were effective in developing early-maturing, high-yielding mutant lines. Similarly, treatments with 0.30%-0.45% EMS, 0.03% nitroso guanidine (NG), and combinations of 300 Gy gamma rays with 0.30% EMS were effective in inducing useful mutations. In proso millet, gamma irradiation identified early-maturing and high-yielding mutants. In barnyard millet, 0.3% EMS and 500-600 Gy gamma irradiations created good variability. In kodo millet, a dose of 0.4% EMS was optimal for recovering viable mutants. In tef, 0.2% EMS for 8 hours induced significant variability and identified candidate mutant lines with aluminium tolerance.

Conventional breeding approaches have successfully characterized millets germplasm and developed numerous cultivars with resistance/tolerance to biotic and abiotic stresses. Genomics-assisted improvement using various omics approaches holds potential for further enhancing genetic gains in small millet improvement.

1.10. Genomics assisted strategies for millets improvement

Genome sequencing provides direct insight into the coding and non-coding regions of the genome that regulate growth, development, and responses to environmental stimuli. The sequence data also aids in developing genome-scale markers, enhancing our understanding of diversity, structure, evolution, and mapping sequence variations linked to specific traits. These markers are crucial for creating molecular tools for genomics-assisted crop improvement. Advances in sequencing platforms have reduced costs while offering greater coverage, depth, and reliability.

For millets, the genomes of foxtail millet, finger millet, proso millet, tef, and Japanese barnyard millet have been sequenced. Additionally, the complete chloroplast genomes of foxtail millet, proso millet, little millet, and barnyard millet are available. Foxtail millet has the smallest genome size (423–510 Mb), whereas finger millet has the largest (1.5 Gb), followed by barnyard millet (*E. crusgalli*, 1.27 Gb). Foxtail millet was the first among millets to have its genome fully sequenced, making it a model for C_4 crop species due to its small diploid genome, short growth cycle, and self-pollinating nature.

Despite the use of next-generation sequencing platforms, most millet genomes remain in draft form and require further resequencing and reannotation to address gaps, mis-annotations, and chromosomal assignments. However, even draft sequences provide valuable information for large-scale genotyping and gene mining. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), in collaboration with Cornell University, genotyped six millets (finger millet, barnyard millet, foxtail millet, proso millet, kodo millet, and little millet) using the genotyping-by-sequencing (GBS) approach. They identified genome-wide single nucleotide polymorphisms and assessed population structure and diversity.

One challenge in sequencing millet genomes is their ploidy levels and high proportion of repetitive DNA. However, the development of third-generation sequencing systems and high-throughput data analysis platforms is expected to overcome these challenges over time. Before the advent of genome sequencing, genes and genomic regions related to traits of interest in millets were mapped using low-throughput markers such as RAPD, RFLP, AFLP, and SSRs. In foxtail millet, Wang et al. (2014) were the first to create an RFLP-based map, identifying a gene on chromosome 8 that significantly affects gamete fertility. Gupta et al. (2011) used RAPD and ISSR markers for germplasm characterization in finger millet. However, the first genetic map, spanning 721 cM on the A genome and 787 cM on the B genome, was constructed by Dida et al. (2007) using a combination of RFLP, AFLP, and SSR markers.

DNA markers (SSR, EST-SSR, ILP, and microRNA-based) developed from foxtail millet genome sequence data demonstrated high cross-genus transferability (over 85%) among other millets such as proso millet, barnyard millet, little millet, and kodo millet, as well as non-millet species. Approximately 62% of switchgrass SSR markers were transferable to proso millet. This high cross-transferability underscores the potential of these markers in germplasm characterization, marker-trait association, and marker-assisted breeding in millets lacking genomic resources.

In well-studied crops like foxtail millet and finger millet, next-generation approaches, including genotyping-by-sequencing (GBS), have been employed to identify quantitative trait nucleotides (QTNs) linked to traits of interest. Jia et al. (2013) constructed a high-density haplotype map in foxtail millet using around 1 million SNPs, identifying 512 loci associated with 47 agronomic traits. Jaiswal et al. (2019) identified SNPs associated with ten yield-contributing agronomic traits and micronutrients in foxtail millet. Similarly, Sharma et al. (2018) and Rajput et al. (2016) identified SNP markers related to important agro-morphological traits in proso millet. Advancements in whole genome sequencing have also enabled direct identification of genes. The availability of genome sequences in public databases like Phytozome, Gramene, and GenBank has facilitated the identification and functional characterization of genes and gene families in sequenced genomes. Foxtail millet, being the first millet to have its genome sequenced, has seen extensive studies on various gene families, including NAC, WD40, AP2/ERF, C2H2 zinc finger, MYB, DCL, AGO, RDR, WRKY, LecRLK, ADP-ribosylation factors, ATG, heat shock proteins and factors, CDPK, and LIM genes. In its wild ancestor, *S. viridis*, the phosphate transporter gene family has been identified and validated.

1.11. Sorghum: Millet or Cereal

Sorghum (*Sorghum bicolor* L.), a very important crop occupying the fifth global ranking in terms of both cultivated acreage and total yield among cereal crops. It is also known as Jowar in India. Sorghum is often considered as a cereal majorly because of the acreage of cultivation (Adebayo Oluwakemi and Omodele 2015). However, in some literature sorghum is also referred to as 'King of Millets'. Keeping this in view a separate chapter on sorghum has been included in this book such that our readers to get a comprehensive idea about crop improvement aspects of millets as a whole.

1.12. Future Scope

Millets have the potential to serve as an alternative or supplement to major cereal staples due to their similar uses in cooking, diverse adaptability to adverse conditions, and nutritional qualities. They can integrate well into multiple cropping systems under both irrigated and rainfed conditions, and their storability under normal conditions has made them valuable as 'famine reserves'. Millets can provide nutritious grains and valuable fodder quickly. However, the limited number of germplasm and inadequate information on genetic diversity restrict their effective use in crop improvement programmes. Therefore, prioritizing germplasm collection is essential to identify specific traits, genes, and alleles for use in breeding programs. So far, millet varieties have been developed mainly through conventional breeding methods. The yield barrier in millets can be broken by a male sterility system and exploiting heterosis, and genomics-assisted crop improvement, together with better crop management and mechanization. Genome assisted breeding will facilitate the identification of novel alleles and genes with superior agronomic performance and resistance to biotic and abiotic stresses to accelerate millets improvement. Biotechnological techniques such as tissue culture and genetic engineering reported in related crops could potentially support millets improvement. The rapid development of sequencing technologies can generate millions of sequences reads at a low cost and in a short time irrespective of whether there is prior sequence