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REVIEW

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Strategies for enhancing productivity, resilience, nutritional quality, and consumption of pearl millet [*Pennisetum glaucum* (L.) R. Br.] for food and nutritional security in India

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Abstract

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is an important component of agri-food system in areas experiencing drought and high temperature and for increasing the resilience to climatic stresses and addressing malnutrition. The purpose of this review is to examine strategies for improving productivity, stress resilience, and nutritional quality of pearl millet and to understand its consumption pattern. Genetic diversification of hybrid parental lines remains strategically important to breed diverse, disease-resistant and drought-tolerant hybrids. Resistance to diseases, tolerance to drought, and high temperature and greater contents of iron and zinc are targeted in improving hybrid parental lines. Lodging resistance, compact panicles, panicle exertion, and improved seed set are universal traits, whereas duration, tillering ability, seed color, and seed size have a strong regional preference. The strategy of developing high-yielding and disease-resistant hybrids with adaptation to challenged agro-ecologies has led to increase in yield from 303 to 1219 kg/ha between 1960 and 2020. Yield and stress resilience are to be increased further using conventional breeding and new tools like genomic selection, speed breeding, genome editing, and precision phenotyping. Mainstreaming grain nutritional traits, viz., iron and zinc contents in genetic improvement are essential to develop high-yielding and nutrient-rich pearl millet. There is need to enhance the consumption of pearl millet by strengthening existing value-chain, providing consumer a choice of diverse range of food products, creating awareness about its health benefits and promotion through government schemes.

Plain Language Summary

Pearl millet is an important component of agri-food system in areas experiencing drought and high temperature. It would have a greater role in future for

Abbreviations: CMS, cytoplasmic male sterility; DM, downy mildew; MSP, minimum support price; QTL, quantitative trait loci; SNP, single nucleotide polymorphism.

increasing the resilience to climate stresses and as nutrient-rich crop for addressing malnutrition. The purpose of this review is to examine strategies for improving productivity, environmental resilience, and nutritional quality of pearl millet and to understand its consumption dynamics. Yield improvement remains a top priority in breeding high-yielding cultivars. Strategies of enhancing yield were influenced by availability of new knowledge and opportunities. Programs up to 1960s focused on the development of open-pollinating varieties using a diverse range of genetic resources. Discovery of cytoplasmic male sterility (CMS), availability of stable male-sterile lines, and effective restorers created new opportunities to exploit heterosis at the commercial scale through the development of hybrids that provided 15%–20% yield advantage over traditional cultivars.

1 | INTRODUCTION

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is a small-seeded C4 crop belonging to the Poaceae family having a high photosynthetic efficiency and dry matter production capacity under the most adverse agro-climatic conditions in the semi-arid and arid ecologies of South Asia and sub-Saharan Africa where other crops like sorghum (*Sorghum bicolour* L. Moench) and maize (*Zea mays* L.) fail to produce economic yields (Serba et al., 2020). Pearl millet is valued for its nutrient-rich grain for human consumption and green fodder and dry stover for livestock. As a result, it contributes to food, nutritional, and livelihood security (Andrews & Kumar, 1992) for more than 90 million people in sub-Saharan Africa and South Asia (Satyavathi et al., 2021). Cultivation of pearl millet is largely concentrated in India, Niger, Sudan, Nigeria, Mali, Burkina Faso, and Chad (FAOSTAT, 2023).

In India, pearl millet is the fourth most important food crop after rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and maize, currently grown over 7.65 million ha (GoI, 2022). It is the most important millet crop in India and the second most important millet in the world after sorghum (FAOSTAT, 2023) and is generally cultivated in areas where annual rainfall ranges between 150 and 600 mm. Pearl millet withstands drought, grows well on less fertile soils, and simultaneously responds well to irrigation and higher fertility levels (Bidinger & Hash, 2004). In India, the major cultivation area is in north-western and central regions, where it is predominantly grown in rainy season (June–September). It is being increasingly cultivated during the summer (February–May) in parts of Gujarat, Rajasthan, and Uttar Pradesh and during the post-rainy (rabi) season (November–February) in Maharashtra and Gujarat at a small scale.

The two most important current challenges in agri-food system are the prevalence of undernourishment of a large section of population and ongoing and projected weather extremes of heat, drought, and precipitation in changing climate (Mirzabaev et al., 2023). Such challenges would be more intense in drylands of India and Africa (Rama Rao et al., 2019; Sultan et al., 2013). Under this scenario, pearl millet has a greater role of play in providing resilience to climatic stresses and nutritious food for farmers and consumers. The purpose of this review is to assess challenges in pearl millet production; examine strategies for improving its productivity, environmental resilience, and nutritional quality; and understand consumption dynamics. Future prospects of improving pearl millet for climate-change scenario and in providing nutritional security are also highlighted.

2 | CHALLENGES

Pearl millet faces a myriad of challenges in cultivation and utilization. Being a dryland and rainfed crop, it confronts drought throughout its crop period. Its cultivation areas fall in tropical and subtropical regions where heat stress during growing season is common and diseases like downy mildew and blast are potential constraints in limiting productivity. Strong policy favor to promote wheat and rice has also pushed back the consumption of pearl millet. There is a significant amount of interplay among challenges, understanding of which is important to design strategies to overcome the challenges.

2.1 | Abiotic stress constraints

Drought is a frequent constraint in the hot arid and drier semi-arid areas as the annual precipitation is low with erratic distribution (Nagaraj et al., 2012). It occurs at any stage of growth, but the probability is less in the early-season (June–July) compared to late-season (August–September). However, the impact of drought depends upon its duration and severity and the stage of crop development (Panjala et al., 2023;

Pinheiro & Chaves, 2011). The recorded yield losses yield losses can be as high as up to 75% (Nagaraj et al., 2012).

High temperature stress during seedling stage quite often occurs along with drought (Panjala et al., 2023). The losses due to heat stress are a function of intensity, duration, and rate of increase in temperature (Reddy, 2023) when the soil surface rapidly dries out after planting and gets hotter in the absence of rain even for a few weeks. A hot seedbed environment during seedling stage is likely, with soil surface temperatures reaching to 62˚C in the arid zone of India (Howarth et al., 1996; Peacock et al., 1993).

The summer pearl millet faces heat stress (>42˚C) during flowering and grain-filling stages resulting in poor seed set with significant yield reduction (Gupta et al., 2015). Soil types in these regions are often coarse textured and less fertile having low organic carbon (0.05%–0.40%) causing poor vegetation cover due to its rapid oxidation by high temperature stress (Kumar et al., 2009).

Core Ideas

- Pearl millet has an important role in increasing climatic resilience of agri-food system and reducing malnutrition.
- Strategies of enhancing yield focused on hybrid development, disease resistance, and genetic diversification.
- Use of adapted germplasm and elite materials proved effective in amalgamating drought tolerance and productivity.
- In future, yield is to be increased along with resilience using conventional, genomics-assisted, and speed breeding.
- There is need to enhance the consumption of nutritious pearl millet by strengthening value-chain and creating awareness.

2.2 | Biotic stress constraints

Pearl millet is generally considered a hardy crop and attacked by only a few diseases and insect pests compared to other major cereals. However, these diseases can cause huge damage to the crop both in terms of grain yield and fodder quality whenever cultivars are susceptible and climatic conditions are favorable for disease development. Downy mildew [*Sclerospora graminicola* (Sacc.) J. Schröt.], blast [*Magnaporthe grisea* (T.T. Herbert) M.E. Barr], rust [*Puccinia substriata* var. *indica* Ramachar & Cumm], ergot (*Claviceps fusiformis* Lov.), and smut (*Moesziomyces penicillariae* Bref. Vanky) are economically important diseases.

Downy mildew infects both foliage and the panicles and is the most important and widespread disease. It has become the most destructive disease after the 1970s because of the cultivation of single cross hybrids over large areas (S. D. Singh, 1995). *Sclerospora graminicola* is heterothallic, and therefore the existence of different mating types leads to the development of new recombinants (Raj & Sharma, 2022). The new isolates are periodically collected and characterized for virulence diversity. The most virulent populations are used in the screening of breeding materials.

Ergot and smut are ovary-replacement diseases and directly affect both grain yield and quality. Both diseases occur sporadically and occasionally (Thakur et al., 2011). Infected florets replaced by ergot sclerotia contain neurotoxic alkaloids that can cause various types of toxin-induced symptoms. The estimated grain yield losses due to ergot and smut are 5%–10% although losses could be higher under favorable conditions. The other diseases such as bacterial leaf spot and leaf streak, leaf spots, false mildew, and maize streak virus are not of economic significance in India. However, the incidence and severity of these diseases may increase under changing production environments and climate change scenario (Thakur et al., 2011).

Blast has emerged as an important disease in the last two decades (R. Sharma et al., 2021) and affected productivity and quality. The changing climatic conditions might have contributed to the increased severity of the disease.

Rust is relatively less important because of its appearance after the grain-filling stage (S. D. Singh & King, 1991). However, substantial losses in grain yield and fodder quality may occur when the disease appears before flowering (Wilson et al., 1996). The large-scale seed production in Telangana and Karnataka states of India in the summer season and overlapping cropping has increased the prevalence and severity of rust. Pathogenic variation has also been observed suggesting that fungal populations must be closely monitored for the emergence of new virulence so that new sources of resistance can be identified.

The major challenge in managing the diseases like downy mildew and blast is the existence of pathogenic variability in pathogens which results in the breakdown of resistance genes deployed in the improved cultivars. The insect pests, viz., shoot fly, stem borer, white grubs, earhead worms, and grey weevil are the key pests of pearl millet in India, whereas millet head miner is an important pest in the Sahel in Africa.

2.3 | Declining food consumption

Pearl millet consumption has declined considerably since the late 1980s (Table 1), despite being one of the cheapest sources of macro- as well as micronutrients (Rao et al., 2006). The

TABLE 1 Consumption (kg/capita/annum) of pearl-millet grain vis-a-vis other cereals in India.

Crop	Rural area			Urban area		
	1987–1988	2011–2012	% Change	1987–1988	2011–2012	% Change
Rice	82.73	73.00	−11.76	64.48	54.75	−15.09
Wheat	58.40	52.32	−10.42	57.18	48.67	−14.89
Sorghum	14.36	2.43	−83.05	6.81	1.58	−76.79
Pearl millet	5.96	2.92	−51.02	1.70	0.97	−42.86
Maize	4.62	1.58	−65.79	0.49	0.12	−75.00
Total cereals	175.20	136.27	−22.22	136.27	113.15	−16.96

Source: GoI (1990, 2014).

consumption of pearl millet declined by 51% in rural and 43% in urban areas (GoI, 2014).

The main reason for declined consumption lies in India's agri-food policy. To ensure nation's food security, the agricultural policy had laid considerable emphasis on the production of high-yielding rice and wheat. Farmers are incentivized through input subsidies and output minimum support price (MSP). The Government of India procures rice and wheat at pre-determined MSP for providing rice and wheat to consumers at ₹3 and ₹ 2 per kilogram, respectively, through public distribution system even in those areas where pearl millet is a staple food. This policy, no doubt, ensured self-sufficiency in rice and wheat but replaced less-remunerative and low-yielding millet crops. Government fixes MSP for pearl millet but rarely procures. The other historical reasons for the decline in pearl millet consumption are its low shelf-life and difficulty in preparing dough from its flour for *chapatis* (flat leavened bread).

3 | STRATEGIES

Climate change is posing a serious threat to global food and nutritional security through negative effects on crop growth and agricultural productivity. The intensity of negative impacts of climate change might increase if appropriate adaptation and mitigation measures are not taken. Adaptation strategies aim to improve the crop productivity, resilience to drought, heat, and diseases and develop biofortified crops with a capacity to produce pearl millet grain with higher micronutrients contents. Pearl millet possesses a remarkable ability to endure prolonged droughts, scorching temperatures, and grows well on nutrient-deprived soils and can be one of the top solutions to boost global food and nutritional security (Satyavathi et al., 2021). Being a C4 photosynthetic pathway crop, pearl millet utilizes more atmospheric CO_2 for biomass accumulation. Therefore, it can help to mitigate the effects of climate change through its low carbon footprint. Strategies are, therefore, designed to enhance abiotic and biotic stress tolerance and develop biofortified cultivars with improved yield potential taking full cognizance of future challenges.

3.1 | Enhancing productivity

Yield improvement per unit of land remains a top priority in breeding using the available limited land resources to meet the global demand for continually increasing human population. Strategies have evolved with the creation of new knowledge offering novel opportunities to enhance yield, which heavily depend on the exploitation of the underutilized variation in genetic resources for production and adaptation for the key novel traits for biotic and abiotic stress-related traits for the unpredictable environments.

3.1.1 | Breeding for high-yielding cultivars

Focus on including the available underutilized diverse global genetic resources in the existing breeding program, improving the gene and genotypic frequencies through classical breeding approaches such as recurrent selection methods (Singh et al. 1988), and hybrid technology using the cytoplasmic male sterility (CMS) should be continued. The target should be maintaining the productivity up to 30 q/ha (Khairwal et al., 2009) and further improve it with an adaptation to diverse agro-climatic conditions. This could be achieved by strengthening the base population through stacking/pyramiding the novel traits by the development of association panel, nested association mapping, and multi-parent advanced generation inter-cross populations for traits/gene(s) discovery of the key traits associated with biotic and abiotic stress tolerance for grain, forage and for dual purposes separately (Gireesh et al., 2021; Scott et al., 2020) for pearl millet improvement.

Discovery of CMS (Burton, 1958) and its restorers (Athwal, 1966) created novel opportunities of breeding hybrids for exploiting heterosis. This led to a quantum jump in productivity (Dave, 1987; Joshi et al., 1961; Yadav, Rai, Rajpurohit et al., 2012). Since then, hybrid development continues to be a high priority in India (Figure 1). The strategy of developing high-yielding hybrids with adequate adaptation to different agro-ecologies has been highly impactful (Yadav & Rai, 2013; Yadav, Rajpurohit et al., 2012; Yadav et al., 2017). Further enhancement in productivity will need a multipronged

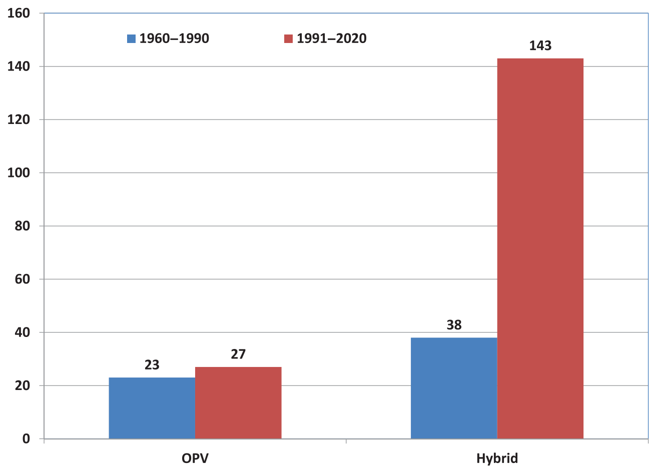

FIGURE 1 Number of open-pollinating varieties (OPVs) and hybrids of pearl millet released during 1960–1990 and 1991–2020.

strategy to accelerate the breeding process and to deliver the improved products. The coming era of breeding must focus on genomic selection, gene editing, and speed breeding to enhance precision and efficiency of selection to develop cultivars for future. Genome sequencing of pearl millet is a major milestone (Varshney et al., 2017) for carrying out trait discovery, mapping, and deployment of quantitative trait loci (QTLs)/alleles/candidate genes linked to traits of economic interests. The whole-genome re-sequencing of Pearl Millet Inbred Germplasm Association Panel, mapping population parents, and elite hybrid parental lines have helped to develop >32 million single nucleotide polymorphisms (SNPs; Jarquin et al., 2020; Srivastava et al., 2020). These developments offer opportunities to rapidly map and deploy genes of agronomic importance and also to rapidly re-sequence lines to mine and map genes of interest. The sequencing-based mapping strategy can also help to identify superior haplotypes for different traits (Sinha et al., 2020). Haplotype-based breeding, forward breeding, genomic prediction, and gene editing would play an important role in future in improving the precision of genetic improvement programs (Varshney et al., 2020).

Delivery of improved products would require a strategic engagement of both public and private sectors. Public sector institutions can focus more on the development of new productive gene pools and germplasm, while the private sector can focus more on product development and testing parts in different agro-ecologies to deliver higher yielding and resource-efficient hybrids.

3.1.2 | Targeting traits

High grain yield with maturity duration of 70–90 days as per the agro-ecological requirements is accorded the highest priority. Due to the growing importance of pearl millet stover for fodder purposes, there is emphasis on breeding for high stover yield in combination with high grain yield (Yadav & Khairwal, 2007). Traits that have regional preferences include plant height of 2–3 m (grain vs. dual-purpose), tillering ability (1–10), seed color (creamy to dark grey), and seed size (test weight of 10–15 g; Rai, Yadav et al., 2012). In diseases, the highest priority has been given to downy mildew resistance, though blast disease has gained increased importance in recent times (R. Sharma et al., 2013).

In the breeding of seed parents, lodging resistance, compact panicles, positive exertion, and good seed set are given high priority in all production environments (Rai, Yadav et al., 2012). These traits of the seed parents are expressed in hybrids to varying levels, depending on the corresponding traits in the pollen parents (Rai et al., 2006). In developing hybrid parental lines, a recessive d_2 dwarf gene is targeted in seed parents breeding due to several operational advantages (Rai & Hanna, 1990; Rai & Rao, 1991). The dwarf lines are lodging resistant in hybrid seed production. The d_2 dwarf male-sterile lines can produce medium-to-tall hybrid with variable height depending on the height of pollinator parent (150–180 cm). New plant types in A-lines include lines with long panicles (30–80 cm compared to standard normal of 10–20 cm), thick panicles (40–50 mm diameter compared to standard normal of 20–30 mm diameter), and large seed size (17–20 g of test weight compared to standard normal of 9–12 g; Gupta et al., 2022).

Restorer lines with profuse pollen production that should remain viable at 42–44˚C are desirable. Pollinators of 150–180 cm height and taller than A-lines are bred with built-in attributes of panicle, maturity, and tillering preferred by farmers in the hybrids (Rai et al., 2006). Pollinators must possess lodging and disease(s) resistance. Evaluation of progenies for disease resistance during the course of inbreeding and selection runs concurrent to agronomic evaluation to ensure that hybrid parental lines should finally possess adaptive phenotypic traits and tolerance to abiotic and biotic stresses.

3.1.3 | Cytoplasmic and genetic diversification

Though A1 CMS source had no link with susceptibility to downy mildew or other disease (Anand Kumar et al., 1983; Rai & Thakur, 1995, 1996; Yadav, 1996; Yadav et al., 1993), alternative CMS sources were required to avoid any unforeseen epidemic that might impact any single CMS source. Search for alternative sources of CMS continued, and consequently six new and distinct sources, viz., A2 and A3 (Burton & Athwal, 1967), Av (Marchais & Pernes, 1985), A4 (Hanna, 1989), Aegp (Sujata et al., 1994), and A5 (Rai, 1995) were identified.

Stability of male sterility, defined as ability to set no seed under self-pollination, across different temperature, humidity, season, and locations is essential. It was established that A2 and A3 systems were unstable, limiting the commercial exploitation of these CMS sources (Rai et al., 1996). On the other hand, other new sources, viz., Aegp, A4, and A5 were highly stable (Rai et al., 2009). However, commercial hybrids could not be developed using A4 and A5 CMS systems due to the non-availability of suitable restores. A recent study characterized diverse Asian and African origin/bred pearl millet germplasm and identified promising restorer populations to derive new restorers to use as parents in future crop improvement programs (Patil et al., 2020). Fertility restoration frequency (%) was found to be highest for A1 (86%) followed by A4 (37%) and A5 (7%) CMS systems. The 45 populations under investigation can be utilized to develop new series of restorer lines (Patil et al., 2020). For further increasing the diversity of restorers of A4 and A5 CMS systems, the backcross breeding method has been developed (Rai et al., 2006). Breeding populations with low-to-moderate frequency of restorers can be rapidly increased by recurrent selection (Gupta et al., 2022). Research programs in India also started developing hybrids based on these CMS systems, and a significant number of seed and restorer parents are available. The understanding of the genetics of A4 (Gupta et al., 2012) and A5 CMS (Gupta et al., 2018) also helped in their efficient utilization. The accessibility of these alternative CMS sources is extremely critical in providing resilience against any biotic and abiotic factor that might proliferate on cytoplasmic uniformity of hybrids.

Genetic diversification of hybrid parental lines is critically important for breed diverse hybrids with high productivity. In breeding seed parents, this is achieved by converting agronomically outstanding and good combining inbreds into male-sterile lines. Observing frequency of male-sterile plants (maintainers) in topcrosses of a large number of diverse populations from India and Africa, it was concluded that the A5 CMS system provides the greatest opportunities to male-sterilize selected lines followed by the A4 and A1 CMS systems (Rai et al., 1996). Utilization of germplasm and breeding material from different geographical regions and with considerable morphological diversity has been strategically utilized in seed parent and restorer breeding (Gupta et al., 2022; Yadav, Rai, Bidinger et al., 2012). In the development of seed parents, African germplasm is largely used, whereas locally adapted lines are utilized in restorer breeding. A large number of seed and restorer parents with unique and diverse combinations for earliness and other adaptable traits are now available to produce hybrids studded with targeted combination of traits.

3.2 | Enhancing resilience

3.2.1 | Understanding nature of drought adaptation

Impact on growth and development is influenced by drought timing, severity, and duration (van Oosterom et al., 1995). Drought immediately after planting leads to seedling mortality, poor crop stand, and reduced yield (Carberry et al., 1985). Drought at the vegetative stage affects tillering ability (van Oosterom et al., 2003; van Oosterom et al., 2006) and flowering initiation (Bidinger et al., 1987a; Kholová et al., 2010; Mahalakshmi et al., 1987; Medina et al., 2017), which are important determinants of productivity. Drought at flowering and post-flowering stages is the most common due to the early cessation of rainfall in the season (Bidinger & Hash, 2004; Kholová & Vadez, 2013; Mahalakshmi et al., 1987; Winkel et al., 1997). The numbers of fertile florets per panicle and grain size are significantly decreased (Bidinger et al., 1987a; Fussell et al., 1991).

Pearl millet exhibits differential response to various types of droughts coinciding with different stages of growth and development. Poor plant stand due to drought at the seedling and crop establishment stage can be compensated to some extent by increasing number of tillers (Bidinger et al., 1987b; Mahalakshmi et al., 1987). However, in the case of severe drought in the beginning of season, crop may completely fail and replanting is the only option (Yadav, Rai, Gupta et al., 2012). Pearl millet response to mid-season drought around the vegetative stage is increased tillering to compensate for loss of panicles in the main shoot (Bidinger et al., 1987b) and delay in flowering initiation (Yadav & Weltzien, 2000) which are parts of its adaptation mechanism to drought. Drought during reproductive stage causes maximum loss in yields as there is significant reduction in grain size due to the shortening of the grain-filling period (Bieler et al., 1993; Fussell et al., 1980; Henson et al., 1984). More recent evidence shows that pearl millet adaptation to terminal drought stress depends on soil moisture availability during the grain-filling stages (Grégoire et al., 2024). Water saving mechanisms such as better transpiration efficiency, restricted transpiration during high atmospheric demand, and leaf expansion at a lower threshold of soil moisture can sustain photosynthesis for a continued carbon supply to the grain during the critical period (Choudhary et al., 2019; Vadez et al., 2013). Physiological understanding of water stress underlined dehydration avoidance, stability of cellular membrane, and radiation reflectance (Kholová et al., 2010). Such knowledge of growth and development under drought has helped to identify sensitive stages, understand yield formation process, and develop drought-tolerant cultivars.

TABLE 2 Contribution (%) of yield potential, drought tolerance, and drought escape in determining the yield performance of pearl millet under drought.

Type of genetic material	Yield potential	Drought tolerance	Drought escape	Reference
Landraces	5	73	22	Yadav et al., 2003
Cultivars	0.4–9.3	18–68	23–81	van Oosterom et al., 1995
Breeding material	4–23	41–47	23–37	Fussell et al., 1991
Segregating lines	2–12	36–36	46–56	Bidinger et al., 1987a, 1987b

3.2.2 | Improving drought tolerance

Drought tolerance in terms of agronomic performance is measured as yield obtained under drought which is a function of three factors, viz., yield potential (yield attainable in the absence of drought), tolerance (genetic ability to provide good yield under water stress), and escape (Bidinger et al.,1987b; Bieler et al., 1993). Several studies have indicated the variable contribution of these factors in a wide range of genetic materials (Table 2). Such a situation requires improving all three components. Improving yield potential has been a regular breeding objective in the improvement programs (discussed in Section 3.1). Other two factors are dealt by manipulating traits associated with target performance. For improving tolerance to mid-season drought, tillering is the most important trait that has been strategically manipulated (Yadav & Rai, 2013; Yadav, 2014) as it provides high elasticity to growth and development. The losses to the main shoot due to water stress can be compensated by basal tillering (Winkel et al., 1997). Existence of huge variation among germplasm for this trait and moderately high heritability made this strategy successful (Appa Rao et al., 1986; Rai et al., 1997; Yadav et al., 2017).

The earliness is the most effective trait in determining performance under late-season or terminal drought, enabling crop to mature before severe stress sets in (Bidinger et al., 1987b; Fussell et al., 1991; Van Oostrerom et al., 1995). The most exploited source of earliness is the Iniadi landrace of western Africa (Andrews & Kumar, 1996). Genetic variation for earliness is widely available in a good genetic background of germplasm (Rai et al., 1997; Yadav et al., 2017), and thus selection is highly effective (Rattunde et al., 1989) to develop early maturing and productive cultivars. Given that pearl millet is prone to drought during all stages of growth and development, breeding programs are sensitive to ensure evaluation in multi-locational target population of environment which is done by delineating specific geographical zones with the occurrence of a particular stress pattern (Gupta et al., 2013).

Use of adapted germplasm is an important strategy to develop drought-tolerant lines (Ceccarelli & Grando, 1991; Yadav, 2008). Landraces from dry areas are suitable material that can be used in breeding programs targeting drought tolerance (Yadav & Weltzien, 2000; Yadav, 2010, 2014) and can be a useful source for developing drought-adapted cultivars (Yadav, 2004) and deriving inbred restorer lines for hybrids (Yadav et al., 2009, 2012). High-yielding elite materials having complementary traits with adapted genetic background can be hybridized to combine drought adaptation of Indian landraces with higher productivity potential of elite materials from Africa (Presterl & Weltzien, 2003; Yadav, 2006, 2010; Yadav & Rai, 2011).

During the past more than two decades, significant progress is made in the development of genomic resources, establishment of linkage mapping, and marker-trait association along with the availability of high-throughput genotyping platforms (Srivastava et al., 2020; Semalaiyappan et al., 2023). Major QTLs have been identified for drought tolerance explaining ~32% of phenotypic variation in grain yield under water-deficit conditions (Yadav et al., 2011). This QTL has been fine-mapped using the LG2 QTL near isogenic line (NIL)-derived F2 mapping population. Of 52,028 SNPs that were identified among NILs, a total of 10 SNPs were anchored to the QTL interval and are now being used in breeding programs (Srivastava et al., 2022). Several other validated QTLs (Yadav et al., 2002; Yadav et al., 2004) have been introgressed into parental lines of elite hybrids resulting in the creation of improved version of the hybrids. This is offering new opportunities in applying markers-assisted selection in conventional breeding programs targeting drought tolerance (Srivastava et al., 2022).

3.2.3 | Improving heat tolerance

In the last two decades, pearl millet is being increasingly grown in the summer season under irrigated conditions with high grain yield and superior grain quality. But crop is challenged by a high temperature (>42˚C) during flowering and pollination resulting in reproductive sterility and poor seed set (Djanaguiraman et al., 2018; Gupta et al., 2015) and hence heat tolerance trait at the reproductive stage is more important and to be targeted as a priority trait for improvement. The evaluation of hybrid parents under controlled environment (maximum temperature of 43˚C and minimum temperature of 22˚C) revealed that boot-leaf is more heat sensitive than the panicle-emergence stage (Gupta et al., 2015). The appearance of the boot-leaf indicates the initiation of the reproductive stage and the meiotic processes like microsporogenesis are under progress during this time (Maiti & Bisen, 1978). Hence, screening for flowering period heat tolerance should be done at the boot-leaf stage. Investigations on A-/B-pairs under controlled environment (maximum temperature of 44˚C and minimum temperature of 22˚C) revealed that the female reproductive parts are more heat sensitive than the pollen. The dominant nature of heat tolerance has been indicated which suggests that a hybrid developed with one heat-tolerant parent should be heat tolerant. Hence, from the breeding perspective, the improvement of seed parent (B-lines) for heat tolerance would be a good option as this allows using all the available restorer parents for the development of high-yielding heat tolerant hybrids (Gupta et al., 2015). Significant genetic variation has been observed in breeding material for the ability to tolerate flowering-period heat stress, and a few heat-tolerant high-yielding hybrids have been developed and deployed under high heat stress production ecologies.

3.2.4 | Improving disease resistance

Host plant resistance is the most effective way of controlling the diseases as it does not add to the cost of production for the farming community and also avoids environmental pollution. The relative severity of diseases has changed over the past two decades because of the introduction of a diverse range of hybrids for cultivation in India. Consequently, DM, the most dreaded disease, is now observed only in traces. Meanwhile, severe outbreaks of blast disease have been recorded in India. Thus, blast has attained the status of the most important disease of pearl millet in terms of prevalence and economic losses. These trends and evolving virulence of established pathogens call for the identification of new sources of resistance.

Screening protocols

Availability of pure culture of the pathogen, effective inoculation technique, large variable germplasm, and adequate laboratory, greenhouse, and field facilities are integral components of disease screening protocols. The understanding of biology and epidemiology of major diseases of pearl millet led to the development of effective disease screening protocols resulting in the identification and utilization of resistance sources (Thakur et al., 2011). Both greenhouse and field screening techniques are well established for DM, blast, and rust diseases, whereas smut and ergot screening is largely done under field conditions following artificial inoculation. Greenhouse screening enables large-scale screening of breeding material at the seedling stage against diverse pathotypes-isolates collected from different agro-ecologies, whereas field screening techniques facilitate multi-location testing for the identification of stable resistance sources for use in breeding programs. The establishment of DM hotspots by national programs in different pearl millet-growing regions has been an effective strategy in assessing the disease severity in real-time situations.

Sources of resistance

In view of evolving virulence of DM and blast pathogens, it is essential to identify new sources of resistance effective against different pathogen populations/pathotypes. Pearl millet lines P7-4, P310-17, IP 18292, IP 18293, 700651, IP 6113-2, IP 8418-3, IP 20715-1, IP 9645, IP 11930, IP 5719-3, IP 6193-2, IP 11428, IP 14522-1, IP 17396-3, IP 17396-4, IP 18294, IP 18295, IP 18298, IP 21201–2, IP 9997, TG 4, TG 8, YG 8, and ZG 3 were found to be resistant to downy mildew at 3–11 locations during 2015–2021, indicating resistance stability in these lines. Blast resistance has also been introgressed from the wild accessions of *Pennisetum violaceum* (= monodii Maire) to cultivated pearl millet through pre-breeding at the ICRISAT, Patancheru (R. Sharma et al., 2021). New sources of resistance against specific pathotypes or multiple pathotypes have been identified (Table 3).

Several DM-resistant lines have been strategically used in breeding programs (Table 3). Substantial progress has been made in managing the risk of losses caused by DM and blast by diversifying the hybrid cultivars base by screening the breeding lines against diverse pathotypes of DM pathogen and sharing the elite disease-resistant hybrid parental lines with the private and public sector organizations for hybrid development.

DM resistance program has been accelerated with the identification and introgression of pathotype-specific QTLs in the parental lines of selected hybrid HHB 67 to create its resistant version (Hash et al., 2006). Similarly, two major QTLs governing blast resistance were employed in improving susceptible hybrid HHB 146 (Bollam et al., 2018).

Transcriptomics, the analysis of gene expression at the RNA level, offers new opportunities for the understanding of host–pathogen interactions at the molecular level. Transcriptome analysis of pearl millet × downy mildew interaction led to the identification and selection of 10 transcripts based on their involvement in defense mechanism. These were validated with quantitative reverse transcription polymerase chain reaction (qRT-PCR), which showed a positive co-relation with transcriptome data (Kulkarni et al., 2016). The RNA-Seq was also employed to understand transcript dynamics of compatible and incompatible interaction of pearl millet-blast pathosystem (S. Singh et al., 2022). A candidate gene-based approach can be used to further characterize transcripts responsible for defense response and identify QTL

TABLE 3 Resistance sources to downy mildew, rust, ergot, and smut used in pearl millet breeding.

Disease	Resistance sources	Reference
Downy mildew	P 7 (ICML 12), SDN 503, (ICML 13), 700251 (ICML 14), 700516 (ICML 15), 700651 (ICML 16), P310-17, P7-3, P1449-2-P1, IP 18298, P 1449-2, YL 18 and ICML 22, IP 5407, IP 5719, IP 6113, IP 6193, IP 8418, IP 8707, IP 9645, IP 9692, IP 10151, IP 11930, IP 11943, IP 12374, IP 14522, IP 14537, IP 14542, IP 14599, IP 17396	Thakur et al., 2011 Sharma et al., 2015
Rust	700481-21-B (ICML 17), IP 537 B (ICML 18), IP 11776 (ICML 19), IP 2084 (ICML 20), P 24 (ICML 21), IP 2696 (ICML 11)	Thakur et al., 2011
Ergot	ICMPE 13-6-27 (ICML 1), ICMPE 13-6-30 (ICML 2), ICMPE 134-6-25 (ICML 3), ICMPE 134-6-34 (ICML 4)	Thakur et al., 2011
Smut	SSC FS 252-S-4 (ICML 5), ICI 7517-S-1 (ICML 6), EBS 46-1-2-S-2 (ICML 7), EB 112-1-S-1-1 (ICML 8), NEP 588-5690-S-8-4 (ICML-9), P 489-S-3 (ICML 10)	Thakur et al., 2011
Blast	IP 21187-P1, ICMR 06444, ICMR 11003, ICMR 08111, ICMR 06666, ICMR 11555, ICMR 08222, ICMR 10888, ICMR 11666, ICMR 10999, ICMR 12777, ICMR 11222, ICMR 12666, ICMR 07444, ICMR 08333, HP-Blast- 458, IP8863-1-1, MDMRRC S1-1-136-1-2-1-B, IP 17396-4-1-1, IP 20715-1-1-5, IP 12374-1-1-2, IP 14537-2-1-1, IP 20274-1-2, IP 9157-1-1	Rajan Sharma, ICRISAT (unpublished)

for resistance breeding. Enhancing disease resistance through genome editing or engineering to overexpress the enzymes that are upregulated in the resistant genotype would be a novel and successful strategy.

4 | DEVELOPING NUTRIENT-RICH CULTIVARS

Micronutrient malnutrition affects about 2 billion people worldwide, and the most prevalent micronutrient deficiencies are iron (Fe), zinc (Zn), vitamin A, and iodine (I), which occur particularly among women and children in developing countries. Pearl millet provides higher energy in the form of carbohydrates (about 60%–70%) similar to other cereals such as rice, wheat, maize, and sorghum (Hassan et al., 2021) but is relatively higher in protein and dietary fiber compared to rice, wheat, maize, and sorghum (Ragaee et al., 2006). It is also rich in iron, magnesium, phosphorus, and potassium (Govindaraj et al., 2022). Quality breeding is targeted to enhance key nutritional traits such as protein, amino acids, and micronutrients. Target nutrition traits are prioritized against food-based problems in target areas and vulnerable groups.

4.1 | Nutritional traits in quality breeding

Earlier research showed large variation for protein content in germplasm (Jambunathan & Subramanian, 1988) and breeding lines (Singh et al., 1987). However, no systematic efforts were made to improve protein content, largely on account of negative correlations between protein content and grain yield (F. Singh & Nainawatee, 1999). Due to lower intake of iron and zinc through staple foods, the severity of Fe and Zn deficiency and its associated health consequences, greater emphasis has been given on these two micronutrients in breeding programs.

Various approaches have been adopted to either identify or create new varieties rich in micronutrients. The identification of micronutrients-rich cultivars from the available released and commercial cultivars was the starting point. For example, the evaluation of 18 released open-pollinating varieties (OPVs) showed a large variation (43–70 ppm Fe and 36–50 ppm Zn density). Similarly, 122 commercial hybrids showed 31–62 ppm Fe density and 32–54 ppm Zn density with a highly popular and widely cultivated hybrid (86M86) having the highest level of Fe (60 ppm) and Zn density (50 ppm). Hybrids parents with Fe density exceeding 60 ppm are identified and used to develop high-Fe hybrids with productivity. Breeding lines and germplasm exceeding 100 ppm Fe density and 60 ppm Zn density have been identified (Rai, Govindaraj et al., 2012). The advantage of this approach was that high micronutrient density was available in the high-yielding genetic background. The second approach is the exploitation of existing variation for Fe and Zn density within genetically variable OPVs to develop their improved versions. The first biofortified variety was developed using simple progeny selection from a high-yielding variety (Rai et al., 2014). The third strategy is to develop hybrid parents with high levels of Fe and Zn density through targeted breeding for these traits for their eventual use in breeding high-yielding hybrids with high levels of micronutrients (Yadav & Rai, 2013).

Mainstreaming nutritional traits in breeding are being emphasized now as the cost-effective screening protocols are in place. Similarly, the extent of genetic variation for grain Fe and Zn contents has been quantified in germplasm and elite genetic material; elite genetic material with high Fe and Zn contents has been identified, and there is fair understanding of relationships between grain minerals and agronomic traits (Govindaraj et al., 2024). National testing and cultivar release policy in India has taken a new initiative to push for biofortified pearl millet by setting a minimum level of 57 ppm Fe and 33 ppm Zn contents for releasing new cultivars (AICPMIP, 2018; Rai et al., 2016). After release of Dhanashakti, the first biofortified crop cultivar in India in 2014, 11 more nutrient-rich cultivars have been released in pearl millet (Yadava et al., 2022).

Metabolomics can enhance our understanding of pearl millet nutritional traits. Nutrition profiling of cultivars, identifying and quantifying metabolites, mapping the metabolic pathways involved in the synthesis, and degradation of key nutrients and anti-nutrients are critically important. By incorporating metabolomic data with genomic and phenotypic data, breeders can identify biomarkers associated with desirable nutritional traits. While metabolomics offers significant potential, there are challenges such as the complexity of metabolomic data, the need for advanced analytical technologies, and the integration of metabolomics with other omics approaches. Future research should focus on overcoming these challenges, standardizing protocols, and expanding the application of metabolomics to various aspects of pearl millet nutrition and health benefits. Identified genomic markers and marker traits association through omics approaches in pearl millet for Fe, Zn and proteins (Anuradha et al., 2017; Pujar et al., 2020; Mahendrakar et al., 2020) would expedite the deployment of nutrition traits into elite breeding materials to enhance nutraceutical value of pearl millet.

5 | STRATEGIES TO ENHANCE CONSUMPTION

One of the significant changes in last few decades is reduced consumption of pearl millet due to poor shelf-life of flour, lesser availability of diversified food items, poor value chain, and strong government policies to only promote rice and wheat in food chain through various government schemes. Both research and policy strategies are required to change the scenario to increase pearl millet consumption.

5.1 | Reducing pearl millet flour rancidity

The term rancidity in pearl millet refers to the generation of off flavor and taste in flour after a few days of storage. On the other hand, there is no such issue in the intact grain irrespective of storage time. Rancidity is a result of enzymatic hydrolysis and oxidation of lipids (Sravani et al., 2023). Detailed biochemical studies established that pearl millet grain structure represent a perfect example of compartmentalization (Barrion, 2008) which acts as a barrier between rancidity-causing enzymes and fats as substrate. The polyunsaturated fatty acid-rich germ is deeply engrained in the endosperm of the whole grain (Barrion, 2008; Slama et al., 2020; Sruthi & Rao, 2021) which is arduous to remove to prevent rancidity. Lipase is the foremost player in inducing off flavor in milled flour, though other factors like oxygen, light, storage conditions, lipoxygenase, peroxidase, polyphenol oxidase, polyphenols, and aldehydic and ketonic compounds also contribute to the deterioration of flour quality and shelf-life per se (Rani et al., 2018; Vinutha et al., 2022). One of major reasons for lower consumption and reduced market demand is rancidity.

Strategies to reduce rancidity include devising of post-harvest interventions and exploring genetic interventions. The former include decorticating the grain, extrusion (Onyeoziri et al., 2021), use of antioxidants (Bajaj et al., 2021), thermal/hydrothermal treatment (Vinutha et al., 2022), dry heat treatment (Bouhallel, 2024), hot water blanching and malting (Bhati et al., 2016), pearling (Tiwari et al., 2014), and manipulating storage conditions (Bouhallel, 2024). These interventions have potential role to provide sufficient storage time of flour.

Genetic variation in germplasm for developing rancidity has been explored. B. Sharma et al. (2020) showed HBL-0828-1, BRBC 1005, and HBL 72 as low rancid lines. Further studies established that loss of function of triglyceride lipases (PgTAGLip1 and PgTAGLip2) genes would suppress free fatty acid content and hydrolytic rancidity (Aher et al., 2022). Bhargavi et al. (2024) reported IP 5695 and IP 19334 as low rancid lines based on biochemical indicators from among 255 genotypes from pearl millet germplasm association panel (PMiGAP). In another study, genome-wide computational analysis has been found effective in characterizing 44 genes allied to the phospholipase gene family in high rancid (ICMB 863) and low-rancid (ICMB 95222) lines (Moin et al., 2024). Higher expression of grain-specific *PgPLD-alpha1-1* and *PgPLD-alpha1-5* genes observed in ICMB 863 than in ICMB 95222 signifies the role of these genes in flour rancidity. The expression of *PLD-delta* isoforms was found to be associated with high resilience to arid conditions (Moin et al., 2024). Genome editing, especially CRISPR-Cas9, presents a promising option for silencing LOX activity genes (B. Sharma & Chugh, 2017) to suppress oxidative rancidity (Panda et al., 2024).

Differential effects of combining ability of inbreds and hybrids for rancidity-related traits are recorded (Pallavi et al., 2023). So far, there are no reports of manipulating rancidity-related traits, but initial results are encouraging to initiate genetic improvement programs targeting rancidity.

5.2 | Diversified and value-added products

Various processing interventions like milling, malting, blanching, acid treatment, dry heating, and fermentation are developed to reduce rancidity and increase the shelf life of flour (Rai et al., 2008). Processed pearl millet grains and flour are used to prepare various types of traditional and nontraditional food products further classified into major food categories like porridge, steam-cooked products, breads, beverages, weaning foods, snacks, and several ready-to-eat products (Murty & Kumar, 1995).

5.3 | Nutritious and healthy food

Pearl millet is finding its uses in preparing various types of health foods as it contains a relatively higher proportion of insoluble dietary fiber and is gluten free. Pearl millet contains 4% linoleic acid in its total fatty acids which plays an important role in many physiological functions like platelet aggregation, reducing cholesterol accumulation, and strengthening immune system. Pearl millet is rich in micronutrients (Fe, Zn, and Mg) and amino acids (lysine, threonine, methionine, and cystine) composition supporting body growth.

One of constraints in the commercialization of pearl millet as health food is a misplaced social stigma branding it as poor man's crop primarily because it is grown in marginal environments, where poverty is common. Thus, pearl millet could not make it to the food basket of the urban elite whose consumption choices play a dominant role in the commercialization of any food product. Grain quality and nutritional studies now show that pearl millet grains are more appropriate choice for the nutritional security of the rural and urban poor who have limited access to other sources of dietary components. There is need of building partnerships between food processors and farmer producer's groups and developing attractive food products by food industries through dedicated millet value chains. The Nutri-Hub initiative under the ICAR-Indian Institute of Millet Research, Hyderabad, India, is one such example of making efforts to accelerate product development and adoption by consortia processors in India. International Year of Millets set the stage for commercial opportunity for millets-based products in the global south, and public distribution approach can significantly enhance millet consumption in India.

5.4 | Policy interventions

Policy support from the governments plays a significant role in product and process commercialization, at least in the initial stages when the food products from grains of new crop species have to compete with those from the established crop species. Subsidy on wheat and rice production and procurement plays a big role in their cultivation and marketing. Support of subsidized public distribution system extended to wheat and rice was not available to pearl millet. Thus, there was little incentive for more production as the returns were not economical when increased production led to a drop in grain prices. Rainfed cultivation with negligible external inputs leads to low productivity with large variation in production and grain surpluses across the years. The low volume and inconsistency in grain supplies reduce the dependability on producers for grain supplies, which is very essential for commercialization. Opportunities exist to drastically reduce or even eliminate these uncertainties through governmental policy support for increased and stable production and marketing of pearl millet grain surpluses. Increasing consumption of pearl millet remains the key issue in creating bulk demand. Several central and state government schemes such as supply of pearl millet in "mid-day meal" for schoolchildren and "Integrated Child and Woman Development" are envisaging the increased utilization for proper nutrition to women, children, and people at large, in addition to income security for farmers. Localized procurement and distribution can be efficient while supplying the excess grain to other locations.

The International Year of Millets in 2023 recognizes the potential value of pearl millet, and several promotional campaigns were organized to boost its production and consumption (NAAS, 2022). Government of India has taken initiatives to include millets in the National Food Security Mission and to mainstream the millets in the food chain.

6 | DEPLOYMENT OF IMPROVED CULTIVARS AND IMPACT

A number of cultivars were developed and deployed in different production environments of pearl millet resulting in a 285% increase in productivity from 309 kg/ha in 1960 to 1219 kg/ha in 2020. However, there existed differential gains in productivity in two phases, during last six decades, having their own uniqueness. The first phase from 1960 to 1990 was characterized by a fewer number of cultivars (Figure 1), both open-pollinated varieties and hybrids, largely developed by the Indian public sector breeding program. The choice of cultivars was relatively limited, and there were a few downy mildew epidemics during the early 1970s and mid-1980s (S. D. Singh, 1995). As a result, annual average increase in productivity was 6.8 kg/ha (Figure 2). The next phase witnessed a new seed policy of government of India in the early 1990s permitting marketing of seed by the private sector that led to investment in research and development of pearl millet. A greater priority was given by the national program to hybrid development (Yadav & Rai, 2013). Seed production was considerably strengthened (Yadav et al., 2015). A larger number of genetically diverse and disease-resistant hybrids with niche adaptation were bred and deployed that avoided downy mildew epidemics during the last three decades.

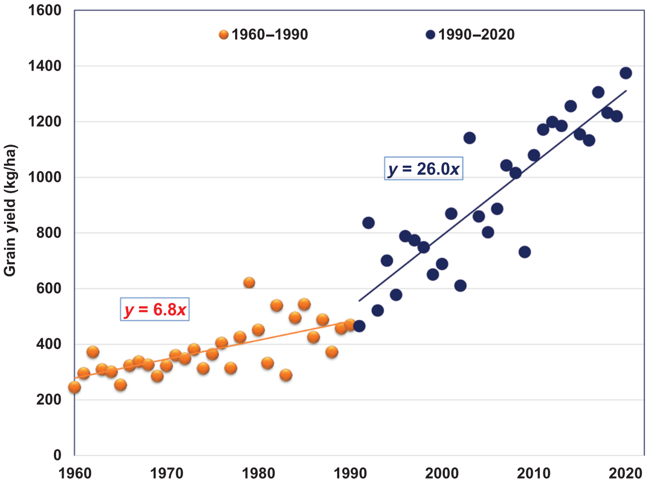

FIGURE 2 Productivity of pearl millet during 1960–1990 and 1991–2020. The figures inside graph indicate increase in grain yield (kg/ha/year).

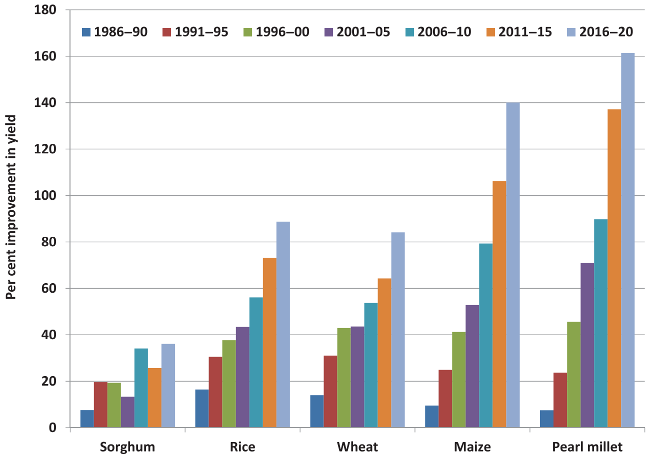

FIGURE 3 Percent yield improvement in sorghum, rice, wheat, maize, and pearl millet from 1986 to 2020 over average yields of 1981–1985.

Consequently, productivity gain of 26.0 kg/ha/year was realized (Figure 2), which is almost four times than that realized during the period of 1960–1990. Yield gains during the last three decades are 36%, 89%, 84%, 140%, and 161% in sorghum, rice, wheat, maize, and pearl millet, respectively (Figure 3). High magnitude of productivity increase in pearl millet assumes greater significance considering that more than 85% of pearl millet is grown as rainfed and often on marginal lands. It also affirms the potential role of hybrid technology in raising crop productivity in marginal drylands.

Among crops, adoption of high-yielding cultivars and seed replacement rate are the highest in pearl millet (Yadav et al., 2019) due to several reasons. First, the availability of cultivars in a range of maturity from 60 days to 90 days provides a wider choice to farmers to select a relevant cultivar as per the length of rainy season of different agro-ecological regions. Second, low seed rate (4–5 kg/ha) requires a modest investment in purchasing hybrid seed which is recovered with as low as 10% higher grain yield with improved cultivars. Third, the procedures with respect to demand generation, production, management, certification, processing, and delivery of improved seed are streamlined to ensure availability of quality seeds of required quantity (Kannababu et al., 2024).

7 | FUTURE PROSPECTS

Present yield levels of pearl millet are five times higher than what they were in the 1950s. A recent analysis indicated that not only yield is increasing, but the rate of increase is going up continually (Yadav et al., 2019). Thus, there is no reason to expect plateauing of yield. However, considering that pearl millet cultivation is likely to become more challenging due to predicted intense drought stress, rise in temperature, and greater disease incidences as the outcome of climate change, yield should be further increased along with the resilience. Impressive genetic gains achieved so far in productivity need to be further accelerated. Fortunately, new opportunities are emerging to achieve next level of jump in productivity.

Genomics-assisted breeding offers a great opportunity by improving the precision and efficiency of the breeding program. The pearl millet genomes sequencing (Varshney et al., 2017) has laid a solid foundation for trait discovery, mapping, and deployment of QTLs/alleles/candidate genes linked to traits governing yield, quality, and environmental adaptation. Several genomics regions for stress tolerance, nutritional quality, and yield-related traits of pearl millet are in place now for their use in genomic-assisted breeding (Papanna et al., 2024). Prediction of hybrid performance using genomic data of parental lines also provides an interesting avenue as has been demonstrated in sorghum (Maulana et al., 2023).

Speed breeding also holds a great promise as traditional breeding methods take about a decade or more to develop a new cultivar. Environmentally controlled facility, known as “RapidGen,” has been developed which will shorten breeding process. Segregating populations are grown at close spacing and under short days for speeding up the growth and development of plants for rapid attainment of homozygosity and reduce the space, time, and resources for line development. This helps in shortening the breeding cycle and increasing the rate of genetic gain without increasing the program size.

Possibility of heterotic grouping in pearl millet seems a reality (Gupta et al., 2020; Papanna et al., 2024) to categorize new hybrid parental lines or germplasm into distinct groups that will help to further enhance the magnitude of heterosis on a long-term basis. Such approach paid huge dividends in maize hybrid development at the global level. A high level of adoption and impact of pearl millet hybrids in the most challenging production ecology of South Asia has dispelled the myth that hybrids are target cultivars for relatively favorable environments to express their potential benefits. Developing hybrids in future with specific adaptation would play an enormously important role for further increasing yields.

Harnessing genetic diversity in more than 23,000 world collections of germplasm from 52 countries including wild species provides a great resource to look for new sources of economic traits, disease resistance, abiotic stress tolerance, and better nutritional quality. A small fraction of germplasm has been utilized so far primarily due to the huge number of germplasm accessions and the presence of desired traits in the unadapted genetic background. The development of core and mini-core collections (Upadhyaya et al., 2011) is helpful to breeders for using desired germplasm in broadening the genetic base of cultivars which is essential to mitigate the effects of climate change and reduce the chances of disease epidemics. Larger availability of molecular tools offers a greater opportunity to transfer a specific targeted region and minimize the linkage drag from agronomically inferior-looking germplasm accessions (B. Sharma et al., 2020).

Amalgamation of higher productivity and nutritious grains is demonstrated to be feasible. But this requires additional traits to be handled in segregating generations and greater resources for nutrient profiling of germplasm and breeding material during course of breeding. Fortunately, no negative association exists between grain yield and micronutrients suggesting the feasibility of combining high yield with a greater concentration of micronutrients. Additional investment in breeding for biofortified pearl millet would ensure that nutrient-rich products are available for consumers.

Consumer taste has not received due recognition during cultivar development. Most of pearl millet is traditionally utilized, but its usage decreased with the enhanced consumption of rice and wheat. Most of the confectionery industries were dominated by rice and wheat and therefore consumer and industry-preferred quality traits and nutritional parameters were standardized for these crops. But such efforts are lacking for all millets including pearl millet. Pearl millet does not produce *chapatis* with the same consistency as wheat does. There is need to bring required cooking and *chapati*-making qualities in pearl millet for easy adoption in daily diet. Exploring the germplasm with better *chapati*-making quality as per consumer preference is the way forward.

Diseases have been managed effectively through genetic resistance and quick replacement of old hybrids with new ones to neutralize the challenges from the evolution of more virulent pathotypes. But this situation makes a case for a continuous monitoring of virulence of DM and blast pathogens. Availability of host differential is essential to identify resistance against virulent pathotypes that might emerge in future. Disease resistance would continue to play a major role in providing resilience in pearl millet production. With the availability of genomic tools, identification of QTLs determining resistance to particular disease, and demonstration of the success of marker-assisted backcrossing (Bansal et al., 2024; Pujar et al., 2023), it now appears possible to stack target QTLs in the parental lines of hybrids having multiple resistance to various pathotypes of downy mildew, blast, and rust.

The need of climate resilient cultivars is greater than ever before in view of looming risks of climate change. Pearl millet is the most drought and heat tolerant, and these attributes put it in an advantageous position to address the multiple environmental challenges which are likely to be of increasingly serious proportion in the future. Precision phenotyping protocols for drought and heat will determine the success of achieving tolerance to multiple stresses. While genotyping has become considerably cheaper and more precise in the recent past, precision phenotyping has been a major challenge. Full advantage of genomic resources can be taken only when quick, accurate, and cost-effective phenotypic data including root systems are available for genetic dissection of drought tolerance and selection of drought-resilient genotypes. Usefulness of high-throughput and automated phenotyping platforms such as LeasyScan has been demonstrated in screening a large number of genotypes for drought tolerance. There exists a much greater need to enhance the capacity for drought tolerance breeding programs to generate quick and accurate data through the use of drones, near-infrared imaging, and remote sensing.

Pearl millet, besides having high iron content, has a low glycemic index and provides several health benefits such as managing blood pressure and cholesterol. In the International Year of Millets 2023, the Government of India has taken several initiatives to make consumers aware of these benefits. Also, there have been a lot of innovations in developing diverse value-added and health products such as cookies, cakes, biscuits, macaroni, pasta, spaghetti, and flakes (NAAS, 2022). The need is to attract private investment in value-addition and processing of pearl-millet and undertake aggressive marketing strategies. The inclusion of its value-added products in the Integrated Child Development Programme and Mid-day Meal Scheme for school children will provide nutritious food to consumers and also create additional demand for pearl millet.

AUTHOR CONTRIBUTIONS

O.P. Yadav: Conceptualization; writing—original draft. **Shashi Kumar Gupta**: Writing—review and editing. **Mahalingam Govindaraj**: Writing—review and editing. **Dhram Singh**: Writing—review and editing. **Aman Verma**: Writing—review and editing. **Rajan Sharma**: Writing—review and editing. **Rajendra Mahala**: Writing—review and editing. **Shivendra Srivastava**: Writing—review and editing. **Pratap Birthal**: Writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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