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REVIEW

Special Section: International Year of Millets

Production and cultivation dynamics of millets in India

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Abstract

Millets gained a great attention at the global level in 2023 which is celebrated as the "International Year of Millets" to create awareness to eventually promote consumption and production. An attempt is made here to understand the cultivation and production dynamics of millets as influenced by their demand and supply. We also assess challenges and emerging opportunities to make millets more productive, competitive, and relevant to future farming. Millets registered a 60% decline in area and a 200% rise in productivity, but production has remained the same during the last seven decades. The demand of millets decreased as food due to greater incentives (purchasing grain at a pre-determined price) and policies (distribution of grains to the public at a subsidized rate) in favor of wheat and rice. Millets would play a greater role in future agriculture due to challenges posed by climate change, limited water supply, and reduced agro-biodiversity. This would need a much greater intensity of investment in millet research and adequate support as extended to wheat and rice. Increased emphasis on their genetic improvement and agronomic management is required to develop cultivars, using new tools and technologies, with high production potential and adequate environmental adaptation to make millets competitive with other crops. Mainstreaming the nutritional traits in millet breeding is also critically important to develop high-yielding cultivars with improved grain quality traits. Promoting millet consumption would remain the key issue for increasing their demand as food, feed, and industrial raw materials through policies and awareness programs. Strengthening of value chain will help in diversifying agri-food production system and creating an ecosystem for millet promotion.

1 | INTRODUCTION

The year 2023 is celebrated globally as the "International Year of Millets" to create health and nutritional awareness about millets to eventually promote their consumption and production. This was in response to the proposal moved forward by India to the United Nations supported by 70 countries in the world.

The Food and Agriculture Organization (FAO) classified millets as small-seeded annual cereal crops grown for food and fodder in regions having characteristically less rainfall. Looking at the highly nutritious nature of millets, this group of crops was declared as "NutriCereals" for production, consumption, and commerce point of view by the Government of India vide notification number F.No. 4-4/2017-NFSM (E) dated April 10, 2018. It includes three major millets, that is, pearl millet (*Pennisetum glaucum* L.), sorghum (*Sorghum bicolour* L. Moench), and finger millet (*Eleusine coracana* L.); five minor millets, that is, foxtail millet (*Setaria italica* L.), proso millet (*Panicum miliaceum* L.), kodo millet (*Paspalum scrobiculatum* L.), barnyard millet (*Echinochloa frumentacea* L.), and little millet (*Panicum sumatrense* L.); and two pseudo millets, that is, buckwheat (*Fagopyrum esculentum* Moench) and *Amaranthus* species.

There is a renewed interest in millets for several reasons. First, millets are highly nutritious (Dayakar Rao et al., 2017), with high calcium, iron, potassium, magnesium, and zinc contents, besides other essential nutrients such as vitamins, amino acids, and fatty acids (Nithiyanantham et al., 2019). Second, millets have in-built tolerance to water stress and supra-optimal temperatures due to their morpho-physiological, molecular, and biochemical characteristics that confer upon better tolerance to environmental stresses than the major cereals (de Vries et al., 2020; Gupta et al., 2017; Yadav et al., 2012). Third, being C_4 crops, millets have greater potential to utilize atmospheric CO_2 for biomass accumulation per unit of water used and thus are recognized as crops with low carbon and water footprints. The short life cycle of millets (10–12 weeks) compared to maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and rice (*Oryza sativa* L.) (16–20 weeks) helps in stress mitigation. Millets are dependable food crops for the resource-poor farmers of dryland regions with uncertain rainfall, short length of the growing period, limited soil moisture, and poor soil fertility, as they are climate-resilient crops (Sukanya et al., 2022). Millets can be grown in a variety of soils, climates, and cropping systems making them a versatile option for farmers. Because of these attributes, millets are considered climate-smart crops. Moreover, as millets are largely produced with low external inputs, especially chemicals, these are considered eco-friendly. Thus, millets can play a vital role in the livelihood of the low-income and malnourished population, provide food and nutrition security, and help achieve the first three sustainable development goals (SDGs) (reducing poverty, zero hunger, good health, and well-being) of the United Nations. However, despite such positive attributes and qualities of millets for present and future agriculture, their cultivation in India and elsewhere has been on decline over the last few decades and hence attracted the attention of policy makers across the world. India celebrated 2018 as the "National Year of Millets" and created greater awareness of the unparalleled attributes of millets.

India has historically been a major producer, consumer, and exporter of millets. There have been significant changes in millet cultivation in India in the last seven decades. An attempt is made here to understand the cultivation and production dynamics of millets. We analyze the role of demand and supply as influenced by policy interventions that swayed both consumption and cultivation. Such long-term experiences from the Indian subcontinent will have a great relevance to Africa and other arid and semi-arid regions where millets are cultivated. In this review, we also assess the emerging opportunities for more productive and competitive future millets farming.

Core Ideas

- There have been significant changes in millet cultivation in India during last seven decades.
- Millets registered a 60% decline in area and 200% rise in productivity.
- Production of millets has remained same during last seven decades.
- Millets would play a greater role in future agriculture due to anticipated challenges posed by climate-change.
- Increasing millet productivity and promoting consumption are the key issues to be addressed.

2 | DATA RESOURCES

Statistical documentation on millets is poorly fragmented (FAO, 2023). The FAO reports country-wise data on millets. The sorghum data are reported separately. The Government of India releases millet data that include pearl millet, sorghum, and finger millet individually, but the other five millets, viz. foxtail millet, proso millet, kodo millet, barnyard millet, and little millet, are grouped as minor millets. The data used in this analysis are obtained from the FAO from 1961 (FAOSTAT, 2023) and the Government of India from 1950 (DAFW, 2023).

3 | CANVAS OF CULTIVATION IN THE WORLD

Millets are recognized among the most ancient food grains and first plants domesticated for food. The earliest evidence of their cultivation found in Indus civilization dates back to 3000 BCE. They are currently grown in 131 countries in over 74 million ha (FAO, 2023) spread across the world but largely concentrated in Asia and Africa (Figure 1). India, Sudan, Niger, Nigeria, and Mali account for 47% of the area. The top millet producers are India, the United States, Nigeria, China, and Ethiopia contributing 53% to production. The

FIGURE 1 Cultivation of millets in different countries in 2020 (red dots).

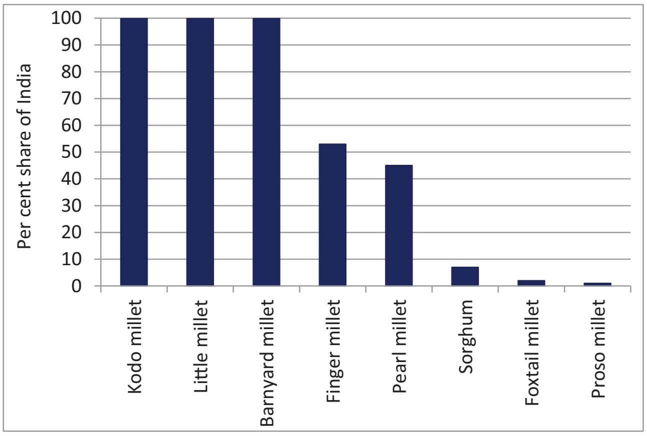


FIGURE 2 Millet crops production (%) in India in 2020.

highest average productivity of millets is achieved by the United States (4.1 t/ha) which is four times higher than the global average (FAOSTAT, 2023).

The total production of millets in the world is 98 million tonnes, with sorghum contributing 63%, followed by pearl millet with a contribution of 24%. The United States produces the maximum sorghum (11.4 million tonnes) with 17% global share. India produces nearly half of the total world production of both pearl millet and finger millet (Figure 2). Kodo millet, little millet, and barnyard millet are exclusively grown in India with a production of 1–3 million tonnes (NAAS, 2022).

Among the millets, sorghum followed by pearl millet and finger millet are important, accounting for nearly 90% share in global millet cultivation and production. India is the largest grower (with 19% contribution) and producer (20% production) of millets in the world. The share of India in Asia stands at 85% in area and 80% in production (FAOSTAT, 2023). Sorghum cultivation is most concentrated in Sudan, Nigeria, India, Niger, and the United States, while India, Niger, Sudan, Nigeria, and Mali are the major growers of pearl millet in the world. Thus, India ranks first in the world with respect to pearl millet cultivation and third in sorghum cultivation (NAAS, 2022).

Millets cultivation has witnessed vast changes. Like other crops, there is enhancement in their productivity from 0.745 t/ha in 1961 to 1.29 t/ha in 2020 registering an increase of 73% due to the development and adoption of new cultivars and agronomic production technology (FAOSTAT, 2023). However, the area under millets declined by 21%. Production increased by 34% during 1960–2020 due to increases in productivity (Figure 3).

4 | CULTIVATION TRENDS IN INDIA

Millets were cultivated in 35 million ha in the 1950s in India which has been reduced to 13.6 million ha in 2020 (Figure 4). The decline in their cultivation was more after the early nineties at an annual decline of over 1%. There has been a consistent increase in their production from 1950 until the mid-eighties. As a result, the production increased 1.4 times between 1950 and 1990 as there was an increase of similar magnitude in productivity with a marginal decline (8%) in the area. Though productivity showed a 73% increase during 2010–2020 in comparison to 1980–1990, production came down by 20% as the area declined by 54% (Figure 4).

The decline in cultivation is variable in different millets (Figure 5). The sorghum area registered a reduction of 70%. The cultivation of minor millets is reduced from 5 to 0.5 million ha registering a 90% decline. Likewise, finger millet area has been reduced from 2.25 to 1.0 million ha. A minimal decline (30%) of the area has been observed in pearl millet which is still grown over 7 million ha (Figure 5) in some of the most harsh and marginal environments of arid and

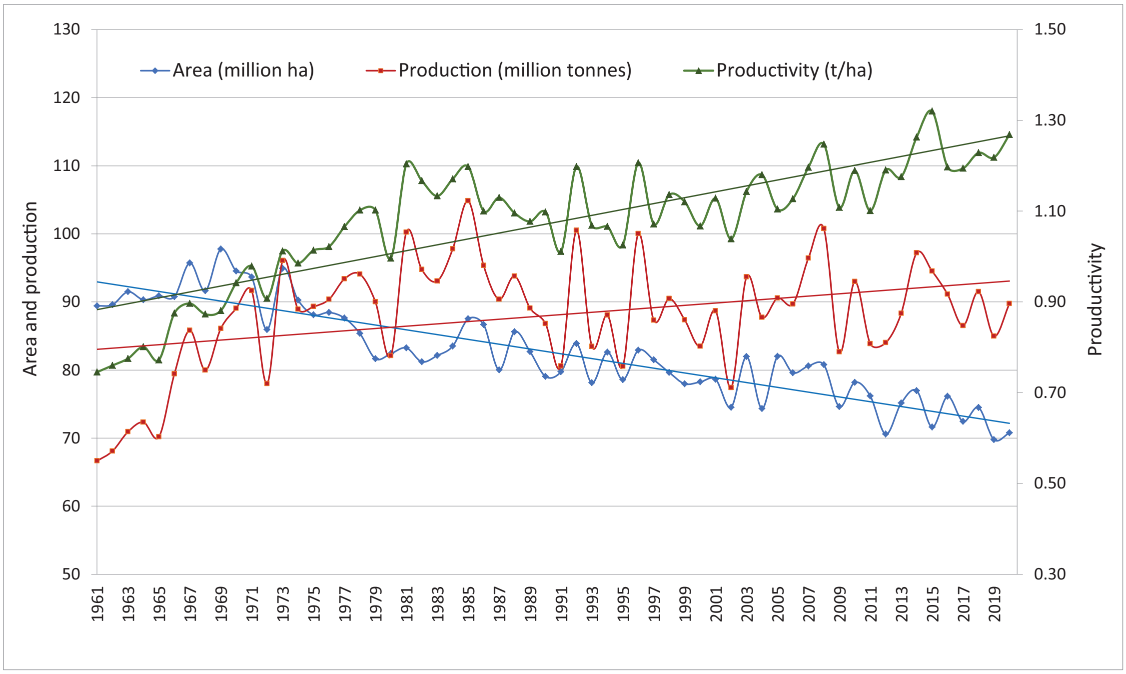


FIGURE 3 The world trends in millets cultivation, production, and mean yields from 1961 to 2020.

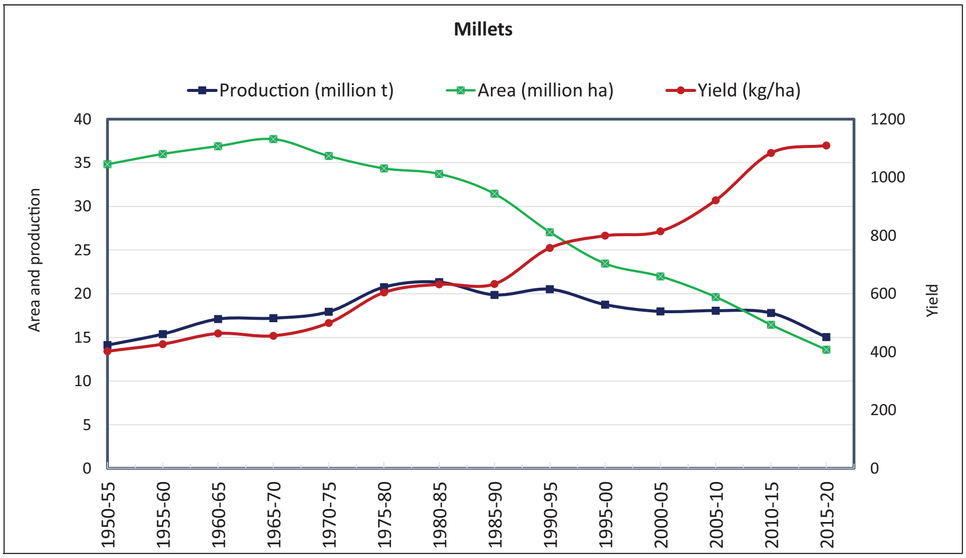


FIGURE 4 Area, production, and productivity of millets in India from 1950 to 2020.

semi-arid regions of north and north-western India (C. T. Satyavathi et al., 2021).

5 | INFLUENCE OF TECHNOLOGY, POLICY, AND DEMAND

There has been a tremendous growth in the productivity of major food crops such as rice, wheat, maize, sorghum, and pearl millet since the mid-sixties (Table 1). Maximum gains in productivity during the period 1963–2020 have been achieved in wheat (3.71 times) followed by pearl millet (3.45 times) in India. The productivity increase during the same period was 2.8 times in maize and 2.6 times in rice. Similarly, productivity was nearly doubled in sorghum, finger millet, and small millets. The progress can largely be attributed to the development and adoption of improved cultivars with higher yield potential and management technologies (Sharma et al., 2022; Yadav et al., 2019).

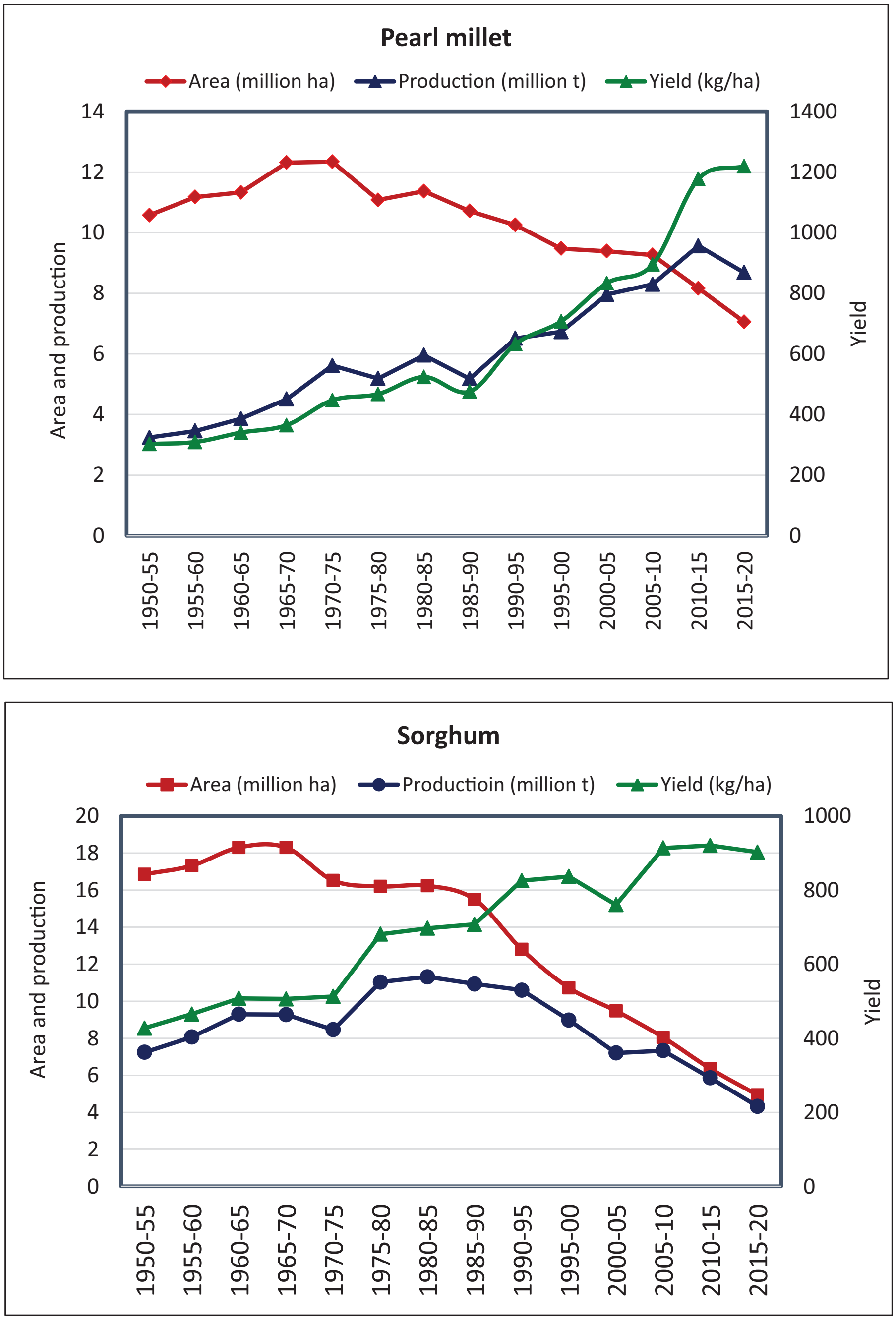
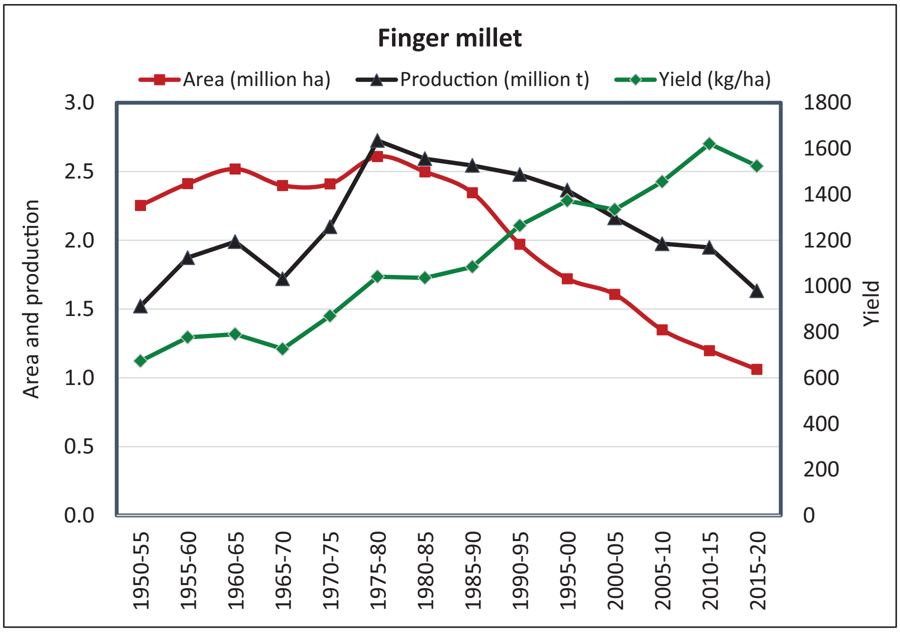


FIGURE 5 Area, production, and productivity of sorghum, pearl millet, finger millet, and small millets in India from 1950 to 2020.

TABLE 1 Area, production, and productivity of wheat, rice, maize, and millets in India since 1963.

Crop	Area (million ha)		Production (million tonnes)		Productivity (kg/ha)	
	1963–1967	2015–2020	1963–1967	2015–2020	1963–1967	2015–2020
Wheat	13.5	30.30	12.1	100.31	892	3311
Rice	35.9	43.84	35.0	112.36	974	2563
Maize	4.9	9.31	5.0	26.72	1019	2866
Pearl millet	12.0	7.34	4.4	9.19	363	1251
Sorghum	18.1	5.10	9.1	4.36	504	864
Finger millet	2.41	1.06	1.77	1.63	746	1524
Small millets	4.64	0.53	1.79	0.39	385	759



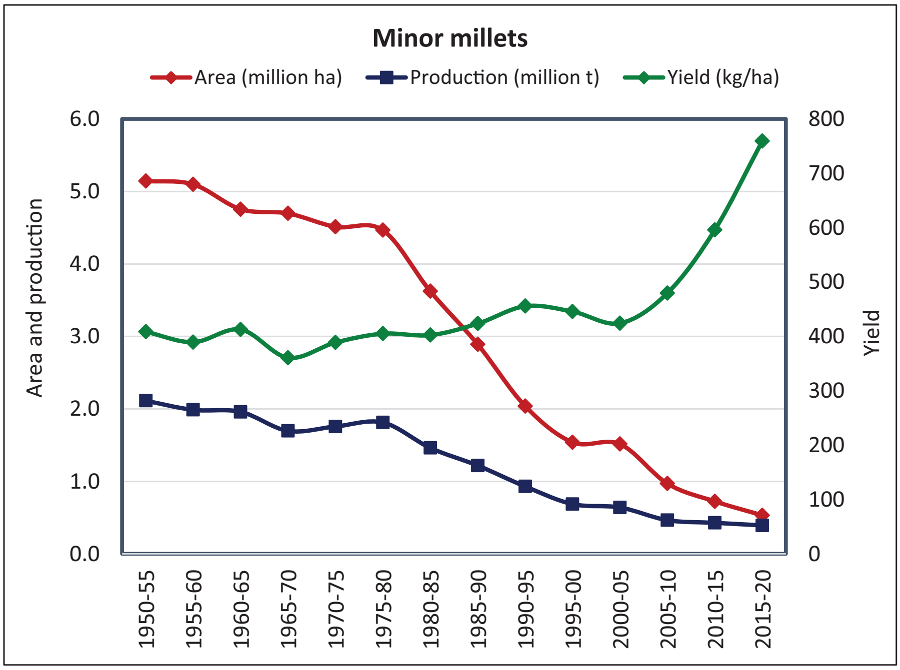


FIGURE 5 Continued

Unlike consistently increasing trends in the productivity of all food crops, the production of individual crops presents a contrasting scenario. Despite 3.7 times yield enhancement in wheat and 2.6 times in rice, acreage under both crops continued to rise (Table 1) as their demand increased (Erenstein et al., 2022; P. Kumar, 1998; A. Kumar et al., 2011). Consequently, farmers got ready market and remunerative prices for their produce. Assurance by the government to farmers of providing minimum support price (MSP) and procurement of wheat and rice grain prompted farmers to grow more of these two crops (Banerjee, 2011; A. Kumar et al., 2011). At the same time, the supply of wheat and rice grain through the public distribution system (PDS) created a mechanism to absorb more production, which helped maintain a balance between the demand and supply of wheat and rice in the market (Banerjee, 2011; P. Kumar, 1998). This arrangement changed India from a food-deficit nation with a population of 0.33 billion in the 1950s to a food-secure nation with about 1.39 billion human population in 2020. This achievement is recognized as the outcome of a "tripartite holy alliance" of the scientists, policy makers, and farmers (Swaminathan, 2013, 2015).

Unlike wheat and rice, although there is no procurement of maize by the government, there is a 90% increase in the area (Table 1) due to a tremendous increase in demand for poultry feed and in starch industries (IIMR, 2015; R. Kumar et al., 2013). The major driving force for maize (Table 1) is market-driven demand (O. P. Yadav et al., 2016). The situation of millets is entirely different from wheat, rice, and maize. For example, an increase in the productivity of pearl millet is equal to that of wheat (Table 1), but cultivation declined due to reduced demand and lack of incentives (Amrinder Reddy et al., 2013). As a result, the land used for pearl millet production was diverted to legumes, cotton, and maize (NAAS, 2022). However, still, pearl millet production doubled despite a 30% decline in the area (Figure 5). The area under sorghum has been continuously declining (Figure 5) due to several reasons. First, lesser improvement in sorghum productivity compared to other crops (Table 1) made it less remunerative (Basavaraja et al., 2005). Second, the demand of kharif sorghum as food almost vanished due to the supply of wheat and rice through PDS (Chand, 2007). As a result, production declined by more than 50% and area by 72% (Table 1). However, *rabi* sorghum sustained to a large extent in post-rainy season (with around 2 million ha acreage) in Maharashtra, Karnataka, and Telangana as there is no other crop that could fit into this production environment (Patil et al., 2014). Hence, there is a need to revisit the priority-setting, re-orient, and strengthen the breeding program in sorghum.

In finger millet, the cultivation decreased by over 50% from the mid-seventies and its production went up by 7.5% due to more than a twofold increase in productivity (Table 1) indicating that the demand of finger millet has remained the same due to its continued preference as food crop. The cultivation of minor millets was 5.14 million ha in the fifties, but a 90% decline in the area resulted in decreased production (80%). Even two times increase in productivity could not compensate for the reduced area (Table 1). The production and cultivation scenario of sorghum and small millets, thus, clearly suggested that the demand of these crops has come down drastically since the 1960s. Thus, the cultivation dynamics of millets as food crops have been influenced by policy interventions extended to rice and wheat, which eventually influence the demand and supply of not only wheat and rice but also millets.

6 | CHALLENGES

Millets have been an important component of farming systems and food baskets in most parts of India. Millets were cultivated in many agro-climatic conditions, particularly in drylands, with low inputs. For centuries, millets were consumed in the form of thick porridge, flat bread, fermented beverages, dumplings, and cooked with vegetables/pulses (P. P. Rao et al., 2006). Only 10%–15% area under millets is irrigated compared to about 95% area under wheat, 60% under rice, and 27% under maize (MAFW, 2023). As they are grown mostly under rainfed conditions, with low inputs (fertilizers, manures, and agrochemicals) because of the high perceived risk of crop failure due to aberrant weather, productivity is low. The productivity of sorghum and pearl millet is about 1.0 and 1.4 t/ha, respectively, which is much lower than that of wheat (3.5 t/ha), maize (3.2 t/ha), and rice (2.8 t/ha) (MAFW, 2023). In good rainfall years, when production is high, farmers do not get remunerative prices due to glut in the market and very little support from the government (Patra et al., 2023). Low productivity and poor price realization lead to less income for millet farmers (NABARD, 2023).

Growing urbanization and provision of wheat and rice under the PDS suppressed the per capita consumption of millets (NABARD, 2023; Prashanthi & Reddy, 2023) that nosedived from 30.9 kg in 1960 to 3.9 kg in 2022 (APEDA, 2022). Despite their nutritional benefits, millets are perceived as poor people's food in many regions, which deters their consumption by the middle and upper classes (B. Srivastava & Reddy, 2023). This perception needs to be changed to enhance their demand. Millets, being coarse, are not as palatable as rice or wheat (Kane-Potaka et al., 2021). Drudgery in primary processing, lack of traditional knowledge in preparing millets, and long cooking time also hinder their adoption (Rai et al., 2008).

Processing of millets is a challenging task due to their small seed size and thick seed coat (B. Srivastava & Reddy, 2023); poor self-life of processed grain and flour (AIM, 2023; Sruthi & Rao, 2021); presence of anti-nutrients such as tannins, phytate, and phenols (Budhwar et al., 2020); and effect of processing techniques on nutritional quality (Gowda et al., 2022). The efficiency of decortication machinery is only 70%–80%, the remaining being the un-hulled and broken grains (B. D. Rao et al., 2021), which creates another challenge of separating un-hulled grains from the dehulled grains. Any one decortication unit is not suitable for all the millets, due to differences in their grain size, shape, and husk content (APEDA, 2022).

Whole millet grains can be stored for over a year even in traditional structures such as mud rhombus, earthen bins or pots, underground pits, and thatch silo. (Mobolade et al., 2019). However, they have poor shelf life after processing due to intrinsic enzyme activity (lipase and lipid oxidation) which causes the rapid development of rancidity and bitterness (AIM, 2023). Millet grains comprise pericarp, germ, and endosperm. The pericarp and germ of millets are rich in lipid content and lipase enzyme (Sruthi & Rao, 2021), which remain separated in whole grain. The lipid content of millets ranges from 1% to 5%, with pearl millet having the highest amount (Sandhu et al., 2018). The lipid in germ comprises a higher amount of triglycerides, which are composed of unsaturated fatty acids. After milling or grinding, the rapid deterioration of lipids occurs due to the action of lipase and, to a lesser extent, by lipoxygenase. The resulting de-esterified unsaturated fatty acids due to subsequent oxidation increase the acidity of flour and also produce a soapy off-flavor (Sruthi & Rao, 2021), which makes the flour unfit for human consumption (G. Zhang & Hamaker, 2005).

Millets have received less attention in agricultural policies and research compared to rice and wheat (NITI Aayog, 2023). The biggest two disadvantages in millets production and consumption, vis-à-vis fine cereals, are their negligible procurement at MSP and the availability of wheat and rice at highly subsidized rates through PDS, despite some efforts of a few state governments and the central government recently. The Central Government of India announces MSP for major millets such as sorghum, pearl millet, and finger millet, along with wheat and rice, but their procurement is very low, limited to a few states. There is not even a notional MSP support for minor millets.

7 | OPPORTUNITIES

The current and future agriculture faces manifold challenges posed by climate change, overexploitation of water resources, and reduced agro-biodiversity (Muluneh, 2021). Malnutrition of a large section of the global population is a major concern (Narayan et al., 2019), and hence millets are of high priority. A myriad of opportunities exist in research, development, and policy that merit the attention of all stakeholders to make millets more relevant in present and future farming.

7.1 | Climate resilience

Greater intensity and frequency of drought in arid and semi-arid regions are predicted to further exacerbate because of imminent climate change (Sultan et al., 2013) which will result in more challenging agro-climatic conditions. This would adversely affect the growth, development, and productivity of crops in the already fragile production environment by reducing the length of the growing period and making seasons more inimical for crops (Rama Rao et al., 2019). Millets offer a greater relative advantage in comparison to other food crops under ever-changing climate as they have an inherent capacity to withstand drought and high-temperature stresses. Their drought resilience can be traced back to their place of origin, domestication, and metabolic pathway and physiology (Pardo & VanBuren, 2021). The Mexican Balsas valley with 1200 mm annual rainfall is the region of domestication of relatively drought-sensitive maize (Pardo & VanBuren, 2021). Sorghum was domesticated in the Sudanese Kassala region with 100–400 mm annual rainfall (Fuller & Stevens, 2018). Pearl millet was domesticated in Sub-Sahara Africa with average rainfall of <400 mm (Harlan, 1971). Other minor millets are indigenous to Southeast Asian climate zones with arid and semi-arid conditions with 400–600 mm rainfall (Baltensperger, 1996; Roshevits, 1980).

Millets have endured traits of adaptation to avoid, tolerate, survive, and produce good economic yields under drought conditions. Pearl millet is a crop of 70–90 days and sorghum of 110 days. Barnyard millet and foxtail millet complete life cycle in 70–80 days, while rice and wheat take about 150–180 days for maturity. Combined with anatomic and physiological adaptations, the dehydration responses allow millets to survive low critical leaf water potential (−1.22 MPa) (Tiwari et al., 2022). The occurrence of stress is evaded by many other traits such as C_4 photosynthetic machinery, fast growth, small leaf area, thickened cell walls, and deep/dense fibrous root system, which maintain water availability and stability during environmental changes (Pardo & VanBuren, 2021). In little millet, shoot length decreased, but root length increased under moisture stress conditions along with significant accumulation of antioxidants, reactive oxygen species scavenging enzymes, superoxide, catalase, glycine betaine, and increased concentration of total free amino acid (Ajithkumar & Panneerselvam, 2014). The ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) of C_4 plants such as pearl millet, sorghum, and finger millet is more efficient in assimilating the CO_2; enhances photosynthetic rates; and confers higher water and nitrogen use efficiency than C_3 crops. The water requirement of millets is lesser than rice, maize, and wheat (*Triticum aestivum* L.) (Saxena et al., 2018).

Considering rising atmospheric temperatures due to climate change (IPCC, 2007), tolerance of crops to high temperatures during reproductive stage has recently assumed a very high significance. A temperature rise of 0.5–1.2˚C in 2020 and a predicted rise of 0.88–3.16˚C and 1.56–5.44˚C, respectively, in 2050 and 2080 have been projected for South Asia (IPCC, 2007). It has also been projected that by the end of the 21st century, mean annual temperatures in India will increase by 3–6˚C (NATCOM, 2004).

The impact of high-temperature stress during the reproductive stage has been studied in many crops. High-temperature stress (>35˚C) for 1 h induced spikelet sterility in rice (Jagadish et al., 2007; Yoshida, 1981). Similarly, temperature higher than 36˚C is reported to reduce pollen viability in maize (Decker et al., 1986) and wheat (Wheeler et al., 1996) causing yield reduction. High temperatures of up to 42˚C tolerance during flowering were reported in pearl millet and sorghum (S. K. Gupta et al., 2015) and occupied considerable cultivable land areas (>2.6 million ha) in the hot and dry post-rainy seasons (March–May) in the northern and western parts of India (Amarender Reddy et al., 2013).

Climate change models have indicated drastic major cereal crops yield reductions in tropical regions with a moderate increase (1–2˚C) in temperature (Sultan et al., 2013). This is likely to result in significant changes in cultivable areas and cropping pattern by replacing maize with sorghum and pearl millet in some semi-arid regions of Asia and Africa due to crop resilience with wider adaptability, nutritional value, and low resource requirements (Sood et al., 2019).

7.2 | Sustainable development goals

The United Nations adopted the SDGs in 2015 as a call to action for the world to end poverty and protect the environment. With millets making a comeback in the International Year of Millets 2023, efforts are being made to achieve the SDGs, particularly SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 12 (responsible consumption and production), SDG 13 (climate action), and SDG 15 (life on land). Millets can be a vital part of a balanced diet and provide an inexpensive supply of iron, protein, dietary fiber, antioxidants, and minerals (Kaur et al., 2021), thereby promoting human health (P. B. Devi et al., 2014; Lei et al., 2006). Agriculture and climate change are strongly connected. Thus, in order to achieve the SDGs targets of eradicating hunger and ensuring food security by 2030, millets play a key role as drought and heat tolerant for SDG 13 (Kaur et al., 2021), reduce carbon footprint of food production (DeFries et al., 2016), are cost-effective and alternative nutrition-rich food crops (Saha et al., 2016), and conserve the water resources (Aravind et al., 2023) to feed a burgeoning global population. Being nutrient rich, millets help to combat malnutrition and achieve Zero Hunger for SDG 2. Millets are gluten-free with a low glycemic index for SDG 3 (Aravind et al., 2023). Millets are fertilizer use efficient for SDG 12 (Devkota et al., 2016) and are comparatively tolerant to insect pests (Saxena et al., 2018). Millets inherently possess the combination of many unique traits satisfying the needs of interlinked SDGs of the UN (Ceasar & Maharajan, 2022).

7.3 | Biofortified food

Nutritional inadequacy due to the lack of micronutrients is a major concern for the expanding global population. Next to major cereals, millets are the most important primary alternative sources of energy in the semi-arid regions and drought-prone parts of Africa and Asia (Hirshi, 2009). A food-based method known as biofortification brings nutrient-rich crops to the doorsteps of poor communities to prevent the growing nutrient deficiency (Bouis et al., 2011).

The HarvestPlus launched conventionally grown pearl millet in India to combat iron deficiency after realizing the value of millet biofortification (Pfeiffer & McClafferty, 2007). Total iron absorption from iron-biofortified pearl millet composite meals was double than regular meals (Cercamondi et al., 2013). An earlier bioefficacy study indicated that students from Indian schools had a 65% decrease in iron deficiency due to the daily intake of 232 g of iron-biofortified pearl millet flour (Pompano et al., 2022). These results support the use of biofortified millets as a sustained food strategy for populations facing a greater risk of iron deficiency.

The significance of millets is recognized in addressing nutritional security in low-rainfall regions. All millets possess a remarkable nutritional profile, making them highly valuable for human consumption as their grains are rich sources of energy, protein, dietary fibers, vitamins, and minerals, including trace elements (Dayakar Rao et al., 2017; Thompson, 1993). Sorghum contains 10.4% protein, 1.9% fat, and 14.3% fiber. The phosphorus, calcium, and iron content in sorghum is 222, 25, and 4.1 mg per 100 g of the edible portion of grain, respectively (Hosmani & Chittapur, 1997). A comparison of proteins among minor millets with rice and wheats showed that proso millet has the highest levels of proteins (12.5 g/100 g), followed by foxtail millet (12.3 g/100 g). In addition, most of the minor millet's proteins are rich in essential amino acids (lysine and tryptophan), which are deficient in rice and wheat. The high levels of resistant starch (>8.0 mg/100 g) in minor millets play an important role in preventing diseases related to dyslipidemia, type 2 diabetes, obesity, and coronary heart disease (M. Muthamilarasan et al., 2015). Among vitamins, foxtail millet is rich in thiamine (0.59 mg/100 g) and proso milletin riboflavin (0.28 mg/100 g) as against rice and wheat (0.04 mg and 0.1 mg per 100 g). Grains from finger millet are rich in calcium (398 mg/100 g), kodo millet for magnesium, (166 mg/100 g), proso millet for copper (5.8 mg/100 g), and little millet for iron (13.0 mg/100 g).

Antinutrients, obstructing the body's ability to absorb nutrients, such as phytic acid, polyphenols, and tannins operate as antioxidants in millet grains (Hama et al., 2012) and significantly lower the bioavailability of minerals (Bravo, 1998; Tako et al., 2015). The processes of fermenting, grinding, malting, roasting, flaking, and decortication are frequently used to eliminate antinutrients (Sheethal et al., 2022). Millets can be processed on a big industrial scale to create innovative functional foods, although these technologies when compared to major cereal crops are not very advanced (Gowda et al., 2022). An intervention diet rich in functional/designer foods derived from millets was associated with a substantial reduction in overall cholesterol, triglycerides, and postprandial blood glucose, as well as pro-inflammatory cytokines and oxidative stress, all of which are significant cardiovascular risk factors for people with diabetes, osteoporosis, and anemia (Anitha, Botha, et al.,2021a; Anitha, Joanna, et al., 2021b). These observations imply that functional foods intervention possibly improves insulin sensitivity, suppresses glucose synthesis, and promotes glucose utilization (Vinoth & Ravindhran, 2017). In order to provide functional foods, millets could be incorporated into

TABLE 2 Germplasm accessions of millets in the gene banks of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, and National Bureau of Plant Genetic Resources (NBPGR), New Delhi, India.

Crop	Number of available accessions in	
	ICRISAT	NBPGR
Pearl millet	25,536	8696
Sorghum	42,880	25,669
Barnyard millet	749	2010
Finger millet	7513	11,666
Foxtail millet	1542	4685
Kodo millet	665	2404
Little millet	473	2226
Proso millet	849	1055
Total	80,207	58,411

bread, pastries, cakes, biscuits, cookies, and other baked goods to supply proteins and the aforementioned micronutrients, potentially reducing the consumption of refined and sweetened foods.

7.4 | Intensifying research

The intensity of research has been historically low in millets in comparison to wheat, rice, and maize (NAAS, 2022). However, a few initiatives have been recently taken by establishing the Indian Council of Agricultural Research (ICAR)-Indian Institute of Millet Research (IIMR), Hyderabad to undertake comprehensive research on production, improvement, and value addition of millets. Global Centre of Excellence on Millets and Technology Business Incubations has recently been established and dedicated fully to promoting millets as a globally competitive climate-resilient nutri-cereal enterprise through value addition (IIMR, 2023).

7.4.1 | Improving productivity to make millets competitive

The average per se productivity of millet crops is lower than major cereals largely because of the cultivation of former in the challenging agro-ecosystem. Therefore, increased emphasis on genetic improvement is required to develop new cultivars using new tools and technologies with high production potential and adequate environmental adaptation to make millets competitive with other crops.

Germplasm utilization: Large germplasm collections (>138,000 accessions) of millets available in the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and National Bureau of Plant Genetic Resources gene banks (Table 2) are core strength to improve millets. Adequate genetic variation has been reported for various agronomic, adaptation, and grain quality traits (Upadhyaya et al., 2006; O. P. Yadav et al., 2017). For better utilization of diversity in crop improvement programs, the concept of core and mini-core collections (Upadhyaya et al., 2014) is key to the strategic utilization of huge wealth of native genetic variation available in the germplasm. The diversification of the genetic base, discovering new traits conditioning tolerance to multiple biotic and abiotic stresses, and yield improvement are essential to make millets more adapted and productive in challenging production environments. The core and mini core collections have been evaluated for agronomic traits, grain nutrients (Upadhyaya et al., 2011), stress tolerance (Krishnamurthy et al., 2014), disease resistance (R. Sharma et al., 2014), and fodder quality traits (Backiyalakshmi et al., 2021). The identified promising trait-specific sources can now be used in enhancing adaptation to challenged agro-production ecologies.

Enhancing yield potential: Millets represent a wide range of opportunities due to different pollination behaviors, available for genetic improvement. The cross-pollinating nature of pearl millet and often-cross pollinated sorghum has permitted hybrid breeding. Heterosis has been exploited for the last six decades in these two crops, and a large number of hybrid cultivars have been released and adopted with significant impact on productivity (Bhat et al., 2023). However, breeding efforts need to be strengthened for drought-prone north-western India for pearl millet and post-rainy season in central India for sorghum to develop hybrids with higher production potential in the challenged agro-ecosystems.

Heterotic grouping of hybrid parental lines and heterosis prediction in hybrids are the priority focus for increased heterosis to realize a significant jump in the productivity of pearl millet and sorghum. Some attempts have been made to define heterotic groups both in pearl millet and sorghum (Maulana et al., 2023; Pucher et al., 2018; Ramya et al., 2018; Sapkota et al., 2023). A study involving 320R and 260B Indian pearl millet parents identified two distinct heterotic groups from each group based on the heterotic performance and combining ability (S. K. Gupta et al., 2020). Hybrids from these identified B × R heterotic groups showed 10% more grain yield heterosis over the best commercial hybrid checks. This study also indicated that distinct parental groups could be formed based on molecular markers, which can help in assigning hybrid parental lines into appropriate heterotic groups to develop high-yielding hybrids. In sorghum, Sapkota et al. (2023) phenotyped 602 hybrids for agronomic performance and genotyped their two female and 301 restorer male parents using 2.69 million single nucleotide polymorphisms for genomic prediction. Genomic best linear unbiased prediction showed that the agronomic performance of hybrids can be predicted with high accuracy, while the prediction of general combining ability of male parents varied from 0.33 to 0.62 for different traits. Both recent studies in pearl millet and sorghum indicate the importance of integrating genomic predictions in hybrid breeding.

Crossing in minor millets is extremely difficult due to self-pollination, smaller flower size, and seed shattering (Sood et al., 2019). As a result, effective pre-breeding and hybridization programs have been challenging. Strengthening of hybridization strategies in minor millets is of high priority to reinforce recombination breeding. Crossing methods such as hot water emasculation, use of Gibberellic acid (GA3), and trifluoromethanesulfonic acid to sterilize the pollen have been found to be effective for recombination breeding. Recently, ICRISAT has performed whole-genome re-sequencing, and a set of 48 SNPs were identified to ascertain true F1s in finger millet (Priyanka et al., 2023).

Genetic gain: Efficiency and precision breeding through integrating high-throughput genomic and phenotypic tools such as speed breeding protocols are needed to accelerate the genetic gains in all millets. The progress in establishing genomic resource of millets has taken a good pace in the recent past. The complete genomes of sorghum, pearl millet, finger millet, and foxtail millet have been made available (Bennetzen et al., 2012; Hatakeyama et al., 2018; Hittalmani et al., 2017; M. Prasad, 2017; Varshney et al., 2017). The reference genome is readily available in proso millet (Zou et al., 2019), whereas limited genomic resources are available in little millet and kodo millet (Habiyaremye et al., 2017; Vetriventhan et al., 2020). These developments in genomic resources offer opportunities to rapidly map and deploy genomic regions of agronomic importance and to rapidly re-sequence lines to mine and map candidate genes of interest. Validation through haplotype analysis would further help to form the basis for haplotype-based breeding to improve genetic gain in many adaptive agronomic traits. Full advantage of genomic resources can be taken only when quick, accurate, and cost-effective phenotypic data can be generated to select stress-resilient cultivars (Tuberosa, 2012). Usefulness of high-throughput and automated phenotyping platforms such as LeasyScan has been demonstrated in screening a large number of pearl millet and sorghum genotypes for drought tolerance (Vadez et al., 2015). LeasyScan is an imaging platform combined with lysimetric capacity to assess canopy traits (leaf area, leaf area index, and transpiration) affecting water use and is based on a novel 3D scanning technique to capture leaf area development continuously, a scanner-to-plant concept to increase imaging throughput and analytical scales to combine gravimetric transpiration measurements (Vadez et al., 2015).

Genetic linkage maps, molecular- or DNA-based markers, and genomic sequences are crucial for marker-assisted selection (MAS). The evaluation of developed QTL related to terminal drought stress tolerance, disease resistance, and adaption traits in millets has been made possible with a number of DNA-based molecular markers (Jogaiah et al., 2014; Kholova et al., 2012). Research focus with collaborative efforts on simultaneous validation through MAS is to be established to accelerate the millet breeding process (R. K. Srivastava et al., 2022).

Integrative marker databases for foxtail millet have been developed which include SiGDB (Duvick et al., 2008), SiFGD (You et al., 2015), FmMDb, FmMiRNADb (B. V. S. M. Muthamilarasan et al., 2013), FmTFDb (Bonthala et al., 2014), and FmTEMDb (C. B. Yadav et al., 2015). Such databases provide complete marker information to the plant science community attempting to produce elite cultivars of foxtail millet. In addition, the genetic variation of proso millet has been investigated using a variety of genetic markers (Habiyaremye et al., 2017). The transcriptomes developed in two proso millet separate accessions revealed almost 35,000 simple sequence repeats and 400,000 single nucleotide polymorphism markers (Yue et al., 2016). Additionally, 833 SNPs from genotype based sequencing data and the reference genome were used in QTL mapping (Zou et al., 2019) and can be used to optimize genomic selection and genomics-enabled prediction in millets. Advancements in genomic tools and their effective integration will improve the prospects of stress-tolerant pipelines through target traits introgression and rapid recycling using a speed breeding platform of adapted millet germplasm/parents in conventional breeding (Bandyopadhyay et al., 2017). Speed breeding has a great potential to enhance genetic gain and accelerate the breeding process in millets. By availing the new environmentally controlled facilities, known as "RapidGen," three to four generations in a year can be accommodated for improved genetic gain in millets.

Sources of native genes conditioning stress adaptation: Millets are genetically tolerant to abiotic stress challenges such as drought, high temperatures, cold, low soil fertility, and salinity (Sood et al., 2019). The available genomic resources from millets can be effectively integrated to improve the climate resilience of wheat and rice (Bandyopadhyay et al., 2017). Sequencing resource from 994 pearl millet lines showed substantial enrichment for wax biosynthesis genes that would contribute to heat and drought tolerance (Varshney et al., 2017). Owing to diploid amenable genome and short life cycle, foxtail millet serves as a model crop for understanding the molecular function of stress-tolerant genes in other crops through comparative genomics (Vetriventhan et al., 2016). In foxtail millet, important transcription factors associated with the response to abiotic stress have been discovered (Feng et al., 2016; L. Zhang et al., 2017). A number of functionally validated drought-tolerant genes such as *SiOPR1*, *DNAj*, *SiPLDa1*, *SiLEA14*, and *SisHSP21.9* (Peng et al., 2010; R. K. Singh et al., 2022; Wang et al., 2009; J. Zhang et al., 2007) and salt-tolerant genes such as *SiREM6* and *SiLTP* (Pan et al., 2016; Veeranagamallaiah et al., 2009) have also been discovered in foxtail millet.

A few stress-responsive genes, such as metallothionein, farnesylated protein ATFP6, protein phosphatase 2A, RISBZ4, and farnesyl pyrophosphate synthase (Parvathi et al., 2013) and transcription factors of 2866 drought-responsive genes (Hittalmani et al., 2017) have been identified to play a major role in imparting drought tolerance in finger millet. The discovery of alleles associated with superior grain nutritional traits will help to introgress the grain quality traits in elite lines through MAS in minor millets. Use of CRISPR-Cas genome editing approach will further help to understand the specific mechanism and transfer such traits to major cereals in the future. Another commonly used approach of exploiting synteny among grass family could be exploited to harness the novel alleles involved in nutrition biosynthesis pathways from millets through utilizing information from well-annotated genomes such as rice.

Enhancing tolerance/resistance to abiotic and biotic stresses: Millets are comparatively less affected by major biotic and abiotic stresses. However, a few diseases and insect pests are causing considerable yield loss, so there is a need for special attention. Downy mildew and blast in pearl millet (Shetty et al., 2016; Thakur et al., 2011); downy mildew and molds in sorghum (Esele, 2003); blast, rust, and smut in foxtail millet (Andersen & Nepal, 2017; Rajesha et al., 2021); sheath blight, bacterial spot, and head smut in proso millet (Santra et al., 2019); grain and head smut and leaf spot diseases in barnyard millet, kodo millet, and little millet (B. Kumar, 2012; Nagaraja et al., 2016) are major diseases. The sources of resistance with a clear understanding of inheritance pattern for these diseases with available effective screening procedures in each crop have also been identified (A. Gupta et al., 2010; Munirathnam et al., 2015; Patro et al., 2018; Thakur et al., 2009, 2007) that need to be used in introgression breeding. Efforts on continuous monitoring of pathogen virulence for new pathotypes and search for new sources of resistance are essential and of paramount importance. Developing diagnostic molecular probes/markers (Madhusudhana, 2020; Ramasamy et al., 2018; O. P. Yadav et al., 2021) and using MAS are needed for developing disease-resistant cultivars.

Although millets have a very high tolerance level to abiotic stresses (Bandyopadhyay et al., 2017; Lata, 2015; Mustaq et al., 2021; Reddy, 2019, 2020; Tadele, 2016; W. Y. Zhang et al., 2012, drought and heat stresses at critical stages are still challenging (Djanaguiraman et al., 2020). These challenges have been dealt in detail earlier (V. B. R. Prasad et al., 2021; R. K. Srivastava et al., 2022; Vetriventhan et al., 2020).

The current defined production ecologies of millets constitute high variations in agro-climatic conditions and are to undergo rigorous quantification of target population environments (TPE) using advanced meteorological databases with high resolution and crop coefficients to accelerate breeding programs addressing abiotic stress tolerance (Aruna & Madhusudhana, 2020). Enhancing crop productivity with less water and under higher temperature regimes is becoming a global necessity.

The exploitation of available germplasm collections for stress environments is relatively meagre for diversifying the cultivar base in TPE. The inclusion of unexplored diverse germplasm of desired maturity range (Upadhyaya et al., 2016) is warranted for continuous use in breeding programs. Further success will depend on the development of repeatable, cost-efficient, high-throughput phenotyping facilities that reliably characterize genetic variation for stress tolerance and its contributing traits.

7.4.2 | Mainstreaming nutritional traits in breeding

The recent research on millets on biofortification has been able to establish that there exists sufficient genetic variation for micronutrients in the germplasm collection of all millets (Rai et al., 2013). Consequently, seed-mineral dense germplasm has been identified in each millet (Govindaraj et al., 2019a). Initial information on the nature and degree of genotype × environment interaction, and inter-relationships between grain minerals and agronomic traits appear to determine breeding efficiency for developing grain mineral dense millet cultivars (Govindaraj et al., 2019b) with high-yielding potential under biotic and abiotic stresses of dryland environments. To propel the mainstreaming of iron and zinc in pearl millet, national testing and cultivar release policy in 2018 is established in India (AICPMIP, 2018; Rai et al., 2013) with significant initiatives in millet breeding (O. P. Yadava et al., 2022) to achieving nutritional security in South Asia and Sub-Sahara Africa.

ICRISAT and Indian National Agricultural Research System have successfully developed 11 high-iron and high-zinc pearl millet varieties and hybrids and introduced in multiple countries. This initiative targeted to develop cultivars with increased micronutrients levels in the ongoing breeding programs.

Cultivars combining high yield potential and better nutritional contents have been developed and deployed in all food crops including millets (Gangashetty et al., 2021; Neeraja et al., 2017; O. P. Yadava et al., 2022). Dhanashakti, the first biofortified crop cultivar in India, was released in 2014 in pearl millet. Since then, 14 more nutrient-rich cultivars have been released in pearl millet, finger millet, and little millet (Table 3), and continuous efforts and investments are needed for other millets.

7.4.3 | Strengthening seed chain

In the last decade, more than 220 cultivars from all millets have been released in India for different agro-ecologies and are being brought in seed production chain to fulfil the needs

TABLE 3 Pearl millet, finger millet, and little millet cultivars released in India and their grain yield and target nutrients and contents.

Crop	Cultivar	Grain yield (kg/ha)	Target nutrients and content	Country
Pearl millet	Dhanashakti	2200	Iron (81.0 ppm) and zinc (43.0 ppm)	India
Pearl millet	Chakti[a]	1420	Iron (62.2 ppm)	Nigeria
Pearl millet	HHB 299	3270	Iron (73.0 ppm) and zinc (41.0 ppm)	India
Pearl millet	AHB 1200Fe	3200	Iron (73.0 ppm)	India
Pearl millet	AHB 1269Fe	3170	Iron (91.0 ppm) and zinc (43.0 ppm)	India
Pearl millet	ABV 4	2860	Iron (70.0 ppm) and zinc (63.0 ppm)	India
Pearl millet	Phule Mahashakti	2930	Iron (87.0 ppm) and zinc (41.0 ppm)	India
Pearl millet	RHB 223	3160	Iron (83.0 ppm) and zinc (46.0 ppm)	India
Pearl millet	RHB 234	3170	Iron (73.0 ppm) and zinc (46.0 ppm)	India
Pearl millet	HHB 311	3170	Iron (83.0 ppm)	India
Pearl millet	HHB 67 Improved 2	2000	Iron (54.8 ppm), zinc (39.6 ppm), and protein (15.5%)	India
Finger millet	VR 929	3610	Iron (131.8 ppm)	India
Finger millet	CFMV 1	3110	Calcium (428 mg/100 g), iron (39.0 ppm), and zinc (25.0 ppm)	India
Finger millet	CFMV 2	2950	Calcium (454 mg/100 g), iron (58.0 ppm), and zinc (44.0 ppm)	India
Little millet	CLMV 1	1580	Iron (59.0 ppm) and zinc (35.0 ppm)	India

[a]Released from Nigeria.

and timely distribution of quality seeds to the farmers. An adequate number of seed-hubs for minor millets foundation seed increase are to be strengthened to increase the adoption of new cultivars and with increased acreage.

To ensure the availability of breeder seed, 18 breeder seed production centers for millets were established in 2018–2019 with the target of enhanced breeder seed availability to various seed production agencies for its downstream multiplication. Further, the quality seed production is targeted through 25 seed-hub sponsored under National Food Security Mission in the next 5 years. In comparison to 26.1 tonnes in 2018–2019, more than 108.0 tonnes of breeder seeds were produced and made available for foundation seed increase. The special efforts in making breeder seed available after National Year of Millets celebrations in 2018 have led to the production of 82,000 tonnes of quality seeds in 2022–2023 as against the demand of 54,000 tonnes.

7.4.4 | Agronomic management

Limited attention has been paid to crop management of millets when compared to the other major cereals (Thilakarathna & Raizada, 2015). The available established crop management strategies, cropping systems, and moisture conservation with clear recommendations for planting time, seed rate, weed management, and fertilizer application including biofertilizers (Bhatnagar et al., 1998) in millets are to be reached and followed by the farmers through collaborative team efforts by extension personnel. Future research priorities should also focus on innovative soil and moisture conservation, integrated nutrient and weed management, crop geometry, precision farming, fodder production, and mechanization to increase their productivity (Sukanya et al., 2022) along with farm digitation and automation for efficient utilization of time and resources.

The results from 300 front-line demonstrations (FLDs) on finger millet, foxtail millet, kodo millet, little millet, barnyard millet, and proso millet conducted across the country recorded 40%, 49%, 58%, 46%, 53%, and 113% increased grain and 34%, 53%, 65%, 27%, 46%, and 103% fodder yields in FLDs, respectively, in the farmers' fields (IIMR, 2021). The productivity of all millets can be easily increased through soil and water conservation, integrated nutrient management, and insect-pests and disease management (Maitra et al., 2020).

Farmers largely grow minor millets by broadcasting a seed mix comprising different species in different proportions as well as intercrop (Bhag Mal et al., 2010). Yield evaluation trials at Kolli Hills in Tamil Nadu and Jeypore in Odisha showed a yield gain of 23%–33% using farmer-selected varieties. Similar trials showed a productivity enhancement of 39% in the case of finger millet, 37% in the case of little millet, and 31% in the case of foxtail millet in the Southern region of India (Bhag Mal et al., 2010). Planting in rows, use of recommended seed rate, and application of farm yard manure resulted in an average increase of 39% in productivity in minor millets (Padulosi et al., 2015).

Millets are mostly grown in low-rainfall areas withstand long dry spells and recover fast after deficit rains with negligible for low input conditions (Sukanya et al., 2023). Farmer-friendly nutrient management practices along with rational cropping systems can play a key role in enhancing productivity (Thilakarathna & Raizada, 2015). Contingency measures such as adjusting planting time, planting geometry, plant population, and nutrient management in different dryland areas are required for the aberrant weather situation (Maitra et al., 2020).

7.4.5 | Postharvest management

Organized procedures and equipment are available to reduce postharvest losses in major cereals; however, millets lack access to such machinery/technologies for harvesting and threshing. Crop-specific machinery must be designed and used taking into account the distinctive morphologies that characterize millet grains. In addition, the grain quality improvements at the producer level include cleaning, dehulling, sorting, polishing, grading, size reduction/grinding, drying, and storage (Birania et al., 2020). Millet grains are routinely dehulled and subjected to various treatments prior to consumption to improve sensory and edible properties. Finger millet cannot be decorticated similar to other grains and can only be used as flour. The hydrothermal treatment stiffened the endosperm texture of millet and allowed for its decortication (Dharmaraj & Malleshi, 2011). However, the nutritional contents of finger millet significantly changed after decortication when they underwent hydrothermal processing.

Grinding pearl millet grains reflected a change in the overall chemical composition (Chowdhury & Punia, 1997). However, the amount of nutrients in raw pearl millet flour did not significantly change because of baking. Furthermore, milling and heat treatment considerably improved the digestibility of carbohydrates and protein while lowering polyphenols and phytic acid (Chowdhury & Punia, 1997). Barnyard millet can be polished in a rice polisher for 3 min with a moisture content of 8%–10% (db) (Lohani et al., 2012). Since the bran fraction of grain is rich in fiber, minerals, and antioxidants and cannot be removed by sifting, it is advised to use whole grains flour in the human diet for better health promotion.

Postharvest handling of small grain-sized millets is a cumbersome process and requires specific machineries for primary (threshing, cleaning, sorting, grading, drying, dehulling, polishing/pearling, grinding) and secondary (puffing, milling, baking, flaking) processing. These postharvest challenges were addressed for efficient handling to reduce drudgery. Multi-millet thresher is developed for the threshing and dehulling of small millets with minimum wastage and high efficiency (Solanki & Goswami, 2023). Several domestic models of threshers suitable for little millet, kodo millet, foxtail millet, proso millet, barnyard millet, and finger millet with threshing capacity up to 100/h with 96% threshing efficiency and less than 2% broken grain are available in the market (Hanumantharaju et al., 2019; K. P. Singh et al., 2015).

Small-capacity dehullers have been developed that are suitable for barnyard millet and foxtail millet with a dehulling capacity of 500 kg/h. However, at the commercial level, industries are using rice dehuller as specially designed large-scale dehullers for millets are yet to be developed (Solanki & Goswami, 2023). Millet value addition machineries have also been developed in the recent past that are suitable for foxtail, little, kodo, proso, and barnyard millets (Solanki & Goswami, 2023).

Despite packing a nutritious punch and possessing commendable biochemical properties, pearl millet is not well-liked by consumers or the food-processing sector since the flour quickly goes rancid when kept for longer than 10 days at room temperature, which results in a short shelf-life (Goswami et al., 2020). Several processing techniques have been utilized to reduce rancidity in stored pearl millet flour and foresee the impacts on nutritional quality, including heat processing methods and dry heat treatment (P. Arora et al., 2002), defatting and antioxidant addition (Kapoor & Kapoor, 1990), gamma irradiation (ElShazali et al., 2011), and hydrothermal treatment (O. P. Yadav et al., 2012). Another holistic approach to address rancidity in pearl millet flour combines ideal pre- and post-processing procedures, involving decortication to remove the oil-rich germ, lowering the pH for the inactivation of enzymes which cause hydrolytic rancidity, defatting by using solvents, use of alternative packaging materials or desiccants and oxygen scavengers in packages, fermentation and malting, use of antioxidants to delay triglyceride auto-oxidation, and microwave treatment (C. Satyavathi et al., 2017). Hydro-treatment, hydrothermal near infrared rays, and thermal treatment were discovered to be efficient processing measures for lowering rancidity in pearl millet flour to prolong the storage up to 90 days at room temperature without affecting the starch, protein digestion, and functional properties (Vinutha et al., 2022). In low rancidity lines, certain polymorphisms in the pearl millet triacylglycerol lipases (PgTAGLip1 and PgTAGLip2) have been identified. With the use of these polymorphisms, hybrid pearl millet types with high yields and longer shelf lives for the flour can be developed. Rancidity in superior milled pearl millet germplasm can be reduced by introducing loss-of-function mutations in TAG lipases using chemical mutagenesis or CRISPR-based techniques (Aher et al., 2022).

7.5 | Promoting millet consumption

Increasing consumption of millets is the key issue for creating their better demand in the food, feed, and industrial market through government schemes, awareness programs, and special research and extension efforts to diversify and promote agri-food production system.

7.5.1 | Food value

Millets grains have been a traditional food for the majority of human population in their cultivation areas (B. D. Rao et al., 2018; Sreekala et al., 2023). Mainstreaming of millets in PDS such as wheat and rice is essential in creating bulk demand. Since different millets are traditional food in different perspectives, regional-based approaches in PDS can also be followed to promote pearl millet in Rajasthan, Haryana, and Gujarat; sorghum in Maharashtra, Karnataka, and Telangana; finger millet in Karnataka; and minor millets in Odisha, Uttarakhand, Madhya Pradesh, and Chhattisgarh. Supplying millets in PDS at a subsidized low price would boost both production and consumption by low-income people (A. Devi et al., 2022). Consumer interest in millets is witnessing some revival with greater health consciousness among the current generation and gaining popularity in the health foods segment (Shah et al., 2023). A survey-based study found that 28% of respondents switched to millets in their regular diets, 15% consuming for weight loss and 14% for taste preferences (Kane-Potaka et al., 2021). The rising health consciousness among educated and middle-class consumers is driving up the demand for nutrient-rich millets and opening new market opportunities (B. Srivastava & Reddy, 2023). Promoting value addition and modernization of the processing sector of millets may encourage urban and high-income households to consume more millets or millets-based food products (A. Devi et al., 2022). These positive trends encourage millet crops cultivation among farmers with increased acreage, production, and more anticipated profits (Padulosi et al., 2015). Utilization of millets in the mid-day meals by the central and state governments is essential not only for augmenting the demand of millets but also for ensuring the proper nutrition to women, children, and people at large, in addition to income security for farmers. Localized procurement and distribution are to be streamlined for efficient and timely supply of the excess grain to other regions in need.

Gluten intolerance, leading to protein allergy, is a physiological disorder in a large population (Hassan et al., 2021). Millets, being gluten-free, have a good chance of being commercialized for the food-based management of this health problem. Promotion of millets as nutri-cereals has opened up new markets and consumer segments for them (NABARD, 2023).

7.5.2 | Feed value

The demands of maize grain for use in multiple industries have merited the search for alternative grains to ease the pressure. The substitution of millet grains in animal feed is slowly gaining momentum in recent years. Substitution with pearl millet, sorghum, and finger millets in the diets of chicken and large ruminants resulted in a positive impact on the performance (Hassan et al., 2021; Hidalgo et al., 2004) because of high feed conversion ratio (Venkateswarlu et al., 2018). Whole pearl millet grain can be included in the broiler diet by up to 50% without having a negative impact on performance (Cisse et al., 2016; Rooney, 2003). Similarly, replacement of corn with pearl millet and sorghum in broilers' diets has led to significant enhancements of growth and feed efficiency (Baurhoo et al., 2011). In addition, feeding pearl millet to laying hens is believed to have additional benefit as the eggs increase omega-3 fatty acids and reduced omega-6 (Jacob, 2015). Finger millet and pearl millets were evidently used to replace conventional grains in the feed of goat and cattle with significant performance improvement (Hassan et al., 2021).

Pearl millet and sorghum are good alternatives to maize in the feed industry with an increased demand and significant lower price when compared to maize in the global market (Basavaraj et al., 2005). Of the total global consumption of millets, 28% is utilized as feed (APEDA, 2022). Pearl millet was the most useful owing to its superior nutritional values. To improve millet feeding value further, a greater understanding and priority collaborative research focus following classical and molecular approaches on key anti-nutritive properties such as kafirin, phenolic compounds, and phytate are needed. There is considerable scope to examine the utility of sorghum and pearl millet as feed for milch cattle and buffalo (NAAS, 2022), and accordingly, the traits are to be addressed in crop improvement programs.

7.5.3 | Fodder value

Crop residues constitute 41%–66% of fodder resources for ruminants in South Asia (Renard, 1997). Pearl millet and sorghum are valued for their dry stover as livestock feed in the cropping and livestock farming system in arid and drier semi-arid regions (Bhat, 2015; Blummel et al., 2003). The economic value of the stover is as much as that of their grain particularly in drought severe years (Amarender et al., 2013). Dual-purpose cultivars are of high preference among the farming community. Adequate dry stover and grain yields of pearl millet and sorghum are the major criteria for the adoption of new cultivars (Kelley et al., 1996) with special emphasis on dual-purpose cultivar development (Blummel et al., 2003; O. P. Yadav & Khairwal, 2007; O. P. Yadav & Singh, 2012). In India, there is a short supply of about 38% green fodder in the summer season. Additionally, multi-cut cultivars grown with protective irrigation provide green fodder throughout the warmer periods of summer and rainy seasons serving as a source of both green and dry fodder for the livestock in the arid and semi-arid regions of India in the rainy season (Bhat, 2015).

7.5.4 | Industrial value

Sweet sorghum varieties have a potential use as a complementary crop to sugarcane, and sugars and starches could be fermented to bioethanol and lignocellulose as value-added chemicals (Hu et al., 2022). The high-energy sorghums are capable of 75%–100% more bioenergy than sweet sorghum. The distilled ethanol finds purposes for various applications such as cooking, lighting, gas engines, and boilers. The bioethanol can be sourced from stalks of sweet sorghum. For instance, ICAR-IIMR and ICRISAT are piloting with industries use of sweet sorghum stalks as feedstock for ethanol production to supplement sugarcane molasses-based ethanol used for blending bioethanol with petrol up to 15% (Umakanth & Bhat, 2013). Production of residual sugars and ethanol from sweet pearl millet is also demonstrated (Crépeau et al., 2016).

Ethanol is the most important fermentation product of grain sorghum, while beverage alcohol is feasible with procedural changes (Aruna et al., 2020). Other possible fermented products include citric acid, lactic acid, riboflavin, antibiotics, and microbial polysaccharides. There are a number of distillation units in India manufacturing potable alcohol from sorghum and pearl millet especially when grain is mold infested (B. D. Rao et al., 2004). The Maharashtra state has given policy support for grain-based distilleries. Millets are also emerging as an alternative source to resistant starch (Kaimal et al., 2021; Punia et al., 2021) and seed proteins (Sachdev et al., 2023).

7.5.5 | Agri-food system

During the last seven decades, more than 19 million hectares have been diverted from millets to maize, cotton, soybean, and rice resulting in the exploitation of water resources and reduced agro-biodiversity (B. D. Rao et al., 2018). Several Indian states such as Assam, Bihar, Chhattisgarh, Karnataka, Madhya Pradesh, Maharashtra, Odisha, Rajasthan, Tamil Nadu, Uttarakhand, and Uttar Pradesh have initiated policies and programs to promote or support millet production and consumption in recent years (NITI Aayog, 2023). Demand for organic food is increasing, and millets are the best option (Sukanya et al., 2022).

In states such as Karnataka, Telangana, and Maharashtra, where water is becoming a serious limitation, there is a need to revive millet cultivation (NAAS, 2022). Millet cultivation can be extended to non-millet growing areas (Shahane & Shivay, 2023; Sukanya et al., 2022). Given the minimum requirements of water (Rawat & Kukreti, 2022), small millets such as kodo, little, and barnyard millets can be successfully grown in the post-kharif fallows with the residual moisture content in the drylands (NAAS, 2022). Even in high rainfall areas, millets can be a choice for uplandsin hilly area (Shahane & Shivay, 2023).

7.5.6 | Export value

India is the largest producer of millets in the world. However, its export volumes are insignificant. Given the widespread malnutrition and health-related issues at the global level, demand zones for millets can be identified to devise a possible mechanism of policy convergence within nations to enhance international trade value.

Millet market is expected to grow over 14 billion USD at a compound annual growth rate (CAGR) of 4.6% up to 2027. The share of organic millets is expected to grow over 29.7% at a CAGR of 5.6%. Asia Pacific is with 40.9% market share followed by the Middle East (32.0%) and Europe (14.1%) (Kumar et al., 2023). The millet packaged food market size was 39.5 million USD in 2022 and is expected to reach nearly 78.5 million USD by 2029, growing at a CAGR of 10.2% (MMR, 2023). Since India is the largest producer of millets, there is tremendous potential to earn foreign currency through the export of value-added millet products as they attract premium price compared to raw grain. It is critical to invest in export promotion activities in key markets across the globe to position brand Indian Millets. Awareness creation needs to be among the top priorities, addressing through large-scale sampling, tasting, and fairs across target countries.

7.6 | Strengthening value chain

Value chain is a complex system that involves farmers, processors, retailers, and consumers. The advanced technologies established in rice, wheat, and maize for crop management, processing, value addition, and exports value chains can be directly followed in millets to achieve the targets. Millet research in the early 2000s focused on production and later shifted to consumption, which established considerable importance to demand creation and promotion through centers of excellences for entrepreneurial development, market linkages, and awareness campaigns (Pandey & Bolia, 2023). The Government of India is undertaking several policies and research initiatives and identified gaps by dealing with the inefficiencies associated with millets value chain.

Quality seed production chain and timely accessibility were established across the country for millets promotion. The backward integration with famers' producer organizations (FPO) is being modeled by ICAR-IIMR to achieve collectivization and vertical integration of value addition and market linkages. Over 100 FPOs with millets specificity are rolled out across the country to become part of modern supply chains in India. FPOs can improve farmers' access to markets but need government support to become part of modern supply chains in India (Merkelova et al., 2009; Trebin, 2014). Farm gate value addition through mechanized processing clusters is subsidized through state millets missions by incentivizing millet cultivation and subsequent procurements connecting farmers with markets.

Institutes such as National Institute of Nutrition and Central Food Technological Research Institute studied the nutritional composition and health benefits through nutrient and clinical evaluations and published the quantitative benefits for labeling purposes. It helped to increase demand for millets and valued millets as more sustainable and nutritious crop (Kaushik et al., 2021). Products evaluated are mainstreamed through public-funded programs on a pilot basis in Telangana, Maharashtra, and Karnataka and are now being rolled out in Integrated Child Development Services programs. Policymakers can use this information to develop regulations for consumer needs, while agricultural producers and retailers can use it for making better marketing decisions (Tran et al., 2022).

Millet processing has been strengthened by diversified postharvest processing and value addition technologies. Millets are now processed into a variety of products, including flour, flakes, and ready-to-eat snacks with more than 100 value-added products with improved shelf-life and palatability. The rural and urban brands from millets by 190 start-ups supported by Nutrihub, ICAR-IIMR with more than 300 brands (Verma & Patel, 2012) are now equally competing with food products from rice, wheat, and corn.

Extensive awareness campaigns on millet production, health benefits, and value addition are being carried out by collaborating with state and central government agencies, private industries, and other stakeholders. It helps to organize cyclathons, walkathons, seminars, workshops, and conventions across the country. The Government of India is raising awareness about millets through trainings, events, seed distribution, and media campaigns. The United Nations declared 2023 as the International Year of Millets 2023 and commemorated the value and importance of the climate-resilient millet crops. India is building partnerships with several national and international organizations such as FAO, World Food Program, and ICRISAT to strengthen the network and value chain linkages at the global level and replicating the model with key 930 strategies (Table 4) in other African countries.

Given the experience of millets cultivation in India for the last several decades, there is a need for all relevant stakeholders (agriculturists, policy makers, academician, researchers, and industry players) to combine all production practices, farm level storage, primary and secondary processing, procurement, transportation, and consumption to help evolve a roadmap and timeline to establish an efficient millet value chain (Pandey & Bolia, 2023).

8 | SUMMARY

Looking at continually declining trends in millet cultivation and anticipated role in providing resilience to climatic stresses and as biofortified nutrient-rich food grains, a special drive has been launched to promote millets by celebrating 2023 as the International Year of Millets by the United Nations. The detailed review presented clearly highlighted the compelling need to integrate and replicate the key model research strategies and innovations established in other major cereals for the improvement of productivity in millets (Table 4). The major challenges are (i) exploiting underutilized available genetic and genomic resources to enhance the yield potential under biotic and abiotic stress dryland environmental conditions, (ii) developing biofortified cultivars and mainstreaming the food chain to emphasize the value and importance of millets, (iii) developing additional demand for millet-based products to establish strong national and international marketing strategies and export value, and (iv) intensifying collaborative research and extension activities at national and international levels with high priorities to achieve the targeted goals.

The high-yielding potential under stress environments is to be amalgamated with grain quality traits. Research focusing on studying the magnitude of diversified wide genetic variation from the available underutilized germplasm resources is

TABLE 4 Strategies for strengthening millet value chain.

Area	Suggestion	Action
Production and procurement	Increase the area under millet cultivation, especially in non-traditional areas	Incentivize cultivation in non-traditional areas and strengthening of existing seed hubs and building backward linkages with FPOs for assured supply
Processing and value addition	Diversifying value addition for higher prices and increased profits for farmers	• Explore advanced technologies for improved processing • New RTE, RTC, and RTS products with advanced techniques – prebiotics, probiotics, composite foods, milk, and meat analogues
R&D efforts on critical gaps	Improving primary processing machinery. Scaling up of secondary processing technologies. Establishing degree of polishing standards	• Improving the primary processing efficiency from 60% to 80% • Standardization of novel value-added products for upscaling and expediting the shelf life studies to improve shelf life from 9 to 12 months
Enabling market linkages	Ensure farmers to have access to high-quality seeds, competitive prices, and markets	Linking start-ups with captive markets such as public-funded programs and industries
Positioning millets in global markets	Building the export specific production cluster and positioning two to three selected millets as champion millets	Allocating the separate HS codes for all millet products and creation of export promotional forums
Transfer of technologies	Strengthening the global value chain on millets with transfer of processing technologies to other nations through South-South Triangular Cooperation for international transfer of technologies	Joint research and development projects, promoting incubation and acceleration support to millet start-ups coupled with private investments
Market intelligence	Mapping the countries for potential trade and exports and analyzing export competitiveness for building the product portfolio with appropriate marketing and branding strategies	Analyzing markets and pushing for targeted exports and aligning with major importers such as China, Japan, Kenya, Belgium, and Italy
Policy advocacy	Mainstreaming millets through price, market, and institutional support	Inclusion in integrated children development scheme and mid-day-meal schemes, incentivized cultivation alongside committed procurement as per MSP

Abbreviations: FPOs, famers' producer organizations; HS, harmonized system; MSP, minimum support price; RTC, ready to cook; RTE, ready to eat; RTS, ready to serve.

to be explored. Simultaneously, focus on studying the nature and degree of genotype × environment interaction, inheritance pattern, and inter-relationships between grain minerals and adaptable agronomic traits has to be intensified to developing high-yielding biofortified millet cultivars (Govindaraj et al., 2019a). Breeding for grain quality translates into adding additional trait in breeding programs and would essentially require strong funding resources and collaborative efforts.

The available genomic resources in sorghum, pearl millet, finger millet, and foxtail millet (Bennetzen et al., 2012; Hatakeyama et al., 2018; Hittalmani et al., 2017; M. Prasad, 2017; Varshney et al., 2017) are to be efficiently integrated with advanced prediction models, high-throughput phenotypic data for genomic selection, QTL development, and validation through haplotype analysis, gene expression, and MAS for discovering new traits and allele mining/conditioning tolerance to biotic and abiotic stresses and nutritional traits improvement in millets. The association of genomic regions with target traits such as terminal drought tolerance, disease resistance, and grain quality traits (Jogaiah et al., 2014; Kholova et al., 2012) needs to be efficiently used to accelerate the classical breeding process. With high-throughput phenotyping protocols (Vadez et al., 2015), millet breeding can be speeded up (R. K. Srivastava et al., 2022) to deliver new products having a combination of traits for various 'target populations of environments'. There exists a much greater need to enhance the capacity of breeding programs to generate quick and accurate data using drones, near-infrared imaging, and remote sensing.

Increasing consumption of millets is the key issue for creating their demand in the market as food, feed, and industrial raw material through government schemes, awareness programs, and efforts to diversify the agri-food production system. Significant efforts with initiatives through several missions are ongoing for promoting millets at the global level. A paradigm shift from food security to nutritional security is expected to have a strong value on the future of millets. Development and policy efforts are critical to invest liberally in export promotion activities in world markets to position brand Indian millets. Awareness creation needs to be among the topmost priorities, addressed through large-scale sampling, tasting, and fairs across target destination countries.

AUTHOR CONTRIBUTIONS

O. P. Yadav: Conceptualization; data curation; formal analysis; investigation; methodology; resources; validation; visualization; writing—original draft; writing—review and editing. **Dhram Singh**: Resources; validation; writing—review and editing. **Vandita Kumari**: Resources; software; writing—review and editing. **Manoj Prasad**: Resources; writing—original draft. **S. Seni**: Writing—review and editing. **Roshan Singh**: Writing—review and editing. **Salej Sood**: Writing—original draft. **Lakshmi Kant**: Writing—review and editing. **B. Rao**: writing—original draft. **R. Madhusudhana**: Writing—original draft. **B. Bhat**: Resources. **S. Gupta**: Writing—original draft. **Devendra Yadava**: Resources; writing—review and editing. **T. Mohapatra**: Writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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