

# Current Breeding Approaches in Pearl Millet to Enhance the Nutritional Quality.

## ABSTRACT

Pearl millet is an important cereal crop as it is powerhouse of nutrition with capability to grow at harsh climatic conditions. It is able to overcome sudden climate changes and other natural disasters which can create food security problem by raising the price of foods there by reduce the availability of food materials. Pearl millet can be an alternative nutritious crop for the poor men which provide enough nutrition for active and healthy life. It is cheap source of nutrition when compared to other major cereal crops. While having its nutrition and health benefits, utilization of this crop is restricted due to some anti-nutrition factors and poor keeping quality.

Therefore, the aim of this review is to provide the information about nutritional profile, health benefits, biofortification, products current breeding approaches and future prospects. Problem of pearl millet in order to bring the great yield potential of this important small grain to producers and consumers.

## Introduction

Pearl millet [*Pennisetum glaucum*(L.) R. Br.] is a highly nutritious warm season cereal crop having a high photosynthetic efficiency and dry matter production capacity with a short life cycle. The genome size is (2352 Mbp), (Bennett, 2000). It belongs to family *Poaceae* and sub family *Panicoideae*. It is assumed to have originated in West Africa (Vavilov, 1950) from where it spread into India and other countries.

Pearl millet is a diploid ( $2n = 2x = 14$ ) in nature and most drought tolerant warm-season cereal crop predominantly grown as a staple food grain, source of feed and fodder. It is nutritionally superior and staple food for millions of people living in harsh environments characterized by erratic rainfall and poor soil. It is the only suitable and efficient crop for arid and semiarid conditions because of its efficient utilization of soil moisture and higher level of heat tolerance than sorghum and maize. Farmers prefer the crop as low cost, low risk option not only by choice but also by necessity. It tolerates low soil pH better than sorghum (Myers, 2002). It also possesses unique genetic predisposition to withstand environmental stress and produce appreciable yield when grown on marginal soils. This is usually grown in the soil with depleted fertility, which receives annual rainfall of 150 mm-750 mm.

In terms of area and production, pearl millet occupies the fourth rank in India after wheat, rice and maize. In India pearl millet is cultivated on about 7.52 million ha area and produced 10.28 million tonnes with an average productivity of 1368 kg per ha (Anonymous, 2020a). The major pearl millet growing States are Rajasthan, Maharashtra, Uttar Pradesh, Gujarat and Haryana contributing 90 per cent of total national production. Most of pearl millet in India is grown in rainy (*kharif*) season (June/July – September/ October). It is also cultivated in the summer season (February – May in parts of Gujarat, Rajasthan and Uttar Pradesh; and during the post-rainy (*Rabi*) season (November – February) at a small scale in Maharashtra and Gujarat.

Rajasthan has the highest area under pearl millet accompanied with the highest production in the country. In Rajasthan, the area under this crop depends on the onset of monsoon whereas. The production is governed by the amount and distribution of the rainfall. The state occupied 4.28 million ha area with a total production of 5.11 million tonnes and average productivity of 1192 kg per ha during 2019-20. The major pearl millet growing districts are Barmer, Jodhpur, Jaipur, Nagaur, Alwar, Sikar, Churu, and Jhunjhunu (Anonymous, 2020b).

Pearl millet is highly cross-pollinated crop due to its protogynous nature and wind borne pollination mechanism, which fulfils the essential biological requirement for hybrid development. Exhibits cytoplasmic genetic male sterility (CGMS), making it possible for the development of a single cross hybrid. Inflorescence is a cylindrical spike consisting of a central rachis on which the groups of spikelets are densely packed. Spikelets bear two types of florets, one being bisexual and the other staminate. The unisexual staminate florets are sessile and born below the bisexual flowers. Having three anthers but lacking female organs. The bisexual floret consists of a single pistil with two feathery stigmas and three anthers enclosed between lemma and palea. The stigma remains receptive for one to two days. In hermaphrodite flowers anthesis starts from apex of the panicle toward the base where as the anthesis of the staminate flowers starts 2-3 days after the anthesis of hermaphrodite flowers. Anthesis occurs throughout the day and night but maximum occurs between 10 pm to mid night. Pollen grains remain viable for 5 (hrs).

Pearl millet is very rich in calories, proteins (6-15%), fat (5-6%), carbohydrates (60-72%), fibre (1-1.8%) and minerals with less amount of HCN, which makes it highly nutritive and palatable crop in comparison with other crops (Fleck, 1981). Micronutrient deficiency has become a global threat and especially, people inhabiting in developing countries who

predominantly feed on cereal diet (wheat and rice) are more prone to this micronutrient malnutrition. Millets are nutri-cereals which can combat this malnutrition. Among all millets, pearl millet is a rich source of essential amino acids and minerals like Fe and Zn content (Anuradha *et al.* 2018). It is also the cheapest source of Fe and Zn as compared to other cereals and vegetables (Rai *et al.*, 2008). As a food crop, pearl millet grain possesses the highest number of calories per 100 grams (Burton *et al.*, 1972), which is mainly supplied by carbohydrates, fats and proteins. Important quality aspects of pearl millet forage are high protein (11.6%), low lignin, high dry matter yield, easy to digestible and possesses less oxalic acid which is an anti-nutritional factor (Hanna *et al.*, 1999).

Pearl millet is also a dual-purpose drought-resistant crop useful for fodder purpose, traditionally grown as a rainfed crop mostly under low fertility conditions. Green fodder of pearl millet is preferred over that of sorghum because of its low HCN content so it can be fed to cattle without harm at any stage of growth. The green fodder of bajra also rates high as it possesses high concentrations of albuminoids, carbohydrates and fat and also it has easy digestibility.

The low production of pearl millet in India leads to the need of developing varieties with stable production irrespective of growing place and time under stress conditions. Information on genetic variability about a crop is a prerequisite for crop improvement programs (Ogunniyan and Olakojo, 2014). Availability of sufficient genetic diversity in the germplasm, which is the basis of all breeding programmes.

### **Nutrition and health benefits of Bajra:**

According to the latest National Family Health Survey (NFHS-5) 2019-21 in India;

•**Children's nutritional status:** 3 percent are overweight, 3 percent are underweight, 36 percent are stunted (short for their age), 19 percent are wasted (thin for their height), and 32 percent are wasted (underweight) (heavy for their height). The two groups of children most likely to be underweight are those with low levels of affluence and those whose moms did not complete high school. Anaemia among children: Sixty-seven percent of children age 6-59 months have anaemia (haemoglobin levels below 11.0 g/dl), which is higher than the NFHS-4 estimate of 59 percent.

•**Micronutrient intake:** In the six months before to the study, 37 per cent of children aged 6-59 months received vitamin A supplements. The day or night before the interview, 47% of kids aged 6 to 23 months ate foods high in vitamin A, and 21% ate foods high in iron.

• **Adult nutritional status:** Between the ages of 15 and 49, 19% of women and 16% of men are overweight. Overweight or obese people make up about the same percentage (24 per cent of women and 23 per cent of men).

• **Anaemia in adults:** 57 per cent of women and 25 per cent of males between the ages of 15 and 49 have anaemia.

Biofertilization of millets is one of the ways for combating hunger by genetically enhancing major food crops to produce more nutrients. It is a multidisciplinary approach that aims to use the full capacity of agricultural development and nutrition science to address the ongoing micronutrient problem.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and Mahatma Phule Krishi Vidyapeeth collaborated on Dhanashakti, a high-iron pearl millet variety that was released in Maharashtra in 2012 and later in India in 2013, making it the first mineral biofortified product of any crop cultivar released in India, spearheaded by the CGIAR's Harvest Plus Program. Dhanashakti has a total iron content of 71 mg and a zinc content of 40 mg per kilogram.

ICRISAT has also created a high-iron pearl millet hybrid (ICMH 1201), which is being marketed by Shakti Vardhak Seed Company under the brand name Shakti 1201, using Truthfully Labelled Seed (self-certification). This hybrid has 75 mg/kg iron and 40 mg/kg zinc (similar to Dhanashakti).

**Table:1, Comparison of nutritional content in crops.**

	Crop
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Contents	Pearl millet	Sorghum	Rice	Wheat
Carbohydrates (g)	61.8	67.7	78.2	64.7
Protein (g)	10.9	09.9	07.9	10.6
Fat (g)	5.43	1.73	0.52	1.47
Energy ( Kcal)	347.0	334.0	356.0	321.0
Dietary fiber (g)	11.5	10.2	02.8	11.2
Calcium (mg)	27.4	27.6	07.5	39.4
Phosphorus (mg)	289.0	274.0	96.0	315.0
Magnesium (mg)	124.0	133.0	19.0	125.0
Zinc (mg)	2.7	1.9	1.20	2.8
Fe (mg)	6.4	3.9	0.60	3.9
Thiamine (mg)	0.25	0.35	0.05	0.46
Riboflavin (mg)	0.20	0.14	0.05	0.15
Niacin (mg)	0.90	2.1	1.70	2.7
Folic acid (µg)	36.1	39.4	9.32	30.1

(Source: NIN, Hyderabad, 2018.)

### Importance of Pearl millet as food:

- **Bajra consumption can help us avoid developing type 2 diabetes.** Diabetes is a chronic disease that affects millions of people all over the world. Sudden spikes in blood sugar are concerning, and dietary choices play an important role in blood glucose regulation. Bajra being an amazing combination of good carbs along with ample amounts of dietary fibre makes an ideal diet for those suffering from diabetes. If you are pre-diabetic or if diabetes runs in your family, you should consume Bajra at least three times a week to provide your body with the benefit of slowly digesting starch that can control glucose and minimise your risk of developing this lifestyle ailment.
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- **Bajra assist in losing weight.** Being overweight comes with various health problems and if you are looking forward to shedding those extra fat, Pearl Millet should top your food choices. Rich in protein, Bajra aids in muscle development, strength, and tissue repair. It's an excellent choice for vegans who want to reduce their carbohydrate intake.
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- **Polycystic ovarian syndrome** is a widespread condition that affects women of all ages, from adolescence to menopausal people. This hormonal imbalance can disrupt not just your health but also your emotions, cause severe exhaustion, and result in undesirable hair growth. Aside from medication, decreasing weight and maintaining a strict eating regimen might help you overcome this disease, and Bajra is one such food source. Pearl

Millet, which is high in iron and fibre, helps to reduce visceral fat (fat around the abdomen), which helps to regulate the menstrual cycle and prevent other lifestyle disorders.



➤ **The heart is a vital organ and a regulated diet** helps it to function at the optimum level. Bajra is a powerhouse of magnesium and potassium which plays a crucial role in dilating blood vessels and facilitating better blood circulation. As this miracle millet is a high source of Omega - 3 fatty acids, plant lignans, and other nutrients, regular consumption of Pearl Millet helps to lower bad or LDL cholesterol, preventing artery blockages.



➤ **It aids in digestion and helps to prevent constipation**, which is an indicator of general health. It's a gluten-free cereal that's perfect for celiac disease sufferers. If you have constipation, eat bajra on a daily basis because the insoluble fibre in it bulks up your stool and controls your bowel motions. Pearl millets are one of the few foods which reduce the acidity of the stomach thereby limiting ulcer formation and discomfort due to frequent bouts of acidity. It makes the stomach pH alkaline and thus reduces the risk of colon cancers.

➤ Pearl millet has a variety of beneficial components and antioxidants, such as phenols, tannins, and phytic acid, which can help prevent stroke, cardiovascular disease, and cancer. In addition to encouraging attractive skin, the catechins and quercetin in Bajra **cleanse the liver, kidneys, and purify the body from within.**

➤ **Dietary bajra improves lung capacity.** It is an excellent winter diet, especially for individuals who suffer from asthma or COPD. Pearl Millet's anti-inflammatory qualities, as well as the inclusion of Omega-3 oils, help to reduce swelling, clear mucus, and improve breathing.

➤ **Bajra diet is a great way to lessen acidity.** Since it is an alkaline food it is an excellent choice for reducing acidity. Gas accumulation can result in a range of health issues, including severe chest pain and a burning sensation in the stomach and oesophagus. Acidity can be managed by following strict dietary standards such as eating bland meals and eating at regular intervals. When bajra is combined with vegetables, it significantly decreases acidity.

- **Bajra is a traditional pregnant meal.** If you are pregnant, Pearl Millet is your must-have cereal, thanks to its rich presence of Vitamin B9 also known as folic acid. **Folate is a** crucial for forming DNA and RNA and is key for producing red blood cells, a major factor that can define the growth rate of the foetus in the pregnancy.
- **Bajra helps in bone fortification.** If you're over 30 and already suffering from joint aches, add Bajra to your diet. This phosphorus-rich millet, when combined with calcium, strengthens bones, reduces joint discomfort, and reduces the incidence of chronic diseases like osteoporosis.
- **Bajra aids in the improvement of vision.** Night blindness is a long-term disorder that can be passed on in some families. Poor eyesight in children and adults can lead to major consequences, and Bajra, which is high in vitamin A and zinc, helps to prevent night blindness, improve eyesight, and lessen other vision-related issues such as macular degeneration and presbyopia.
- **It alleviates weariness.** Sudden tiredness is often a sign of a sluggish metabolism, and the body need immediate fuel in the form of meals. Because Bajra is high in Vitamin B1, it aids in greater nutritional absorption by converting it to Adenosine Triphosphate, or ATP.
- Pearl millet is a nutrient-dense superfood that can help you achieve beautiful skin and strong hair development. **Dietary consistency of this wonderful food strengthens hair follicles and makes the skin glow from within** because to the inclusion of protein, fibre, iron, zinc, folate, and niacin.
- **A regular eating schedule of bajra lowers the chance of dying from inflammatory illness.** Inflammatory disorders include rheumatoid arthritis, gout, asthma, ulcerative colitis, Crohn's disease, and neurological diseases including Alzheimer's and Parkinson's disease. According to the Iowa Women's Health Study, women who ate two or more servings of whole grains per day had a 30% lower risk of dying from an inflammation-related disease.

## **Current breeding approaches followed for developing biofortified varieties of bajra**

### **1. Biofortification breeding approach**

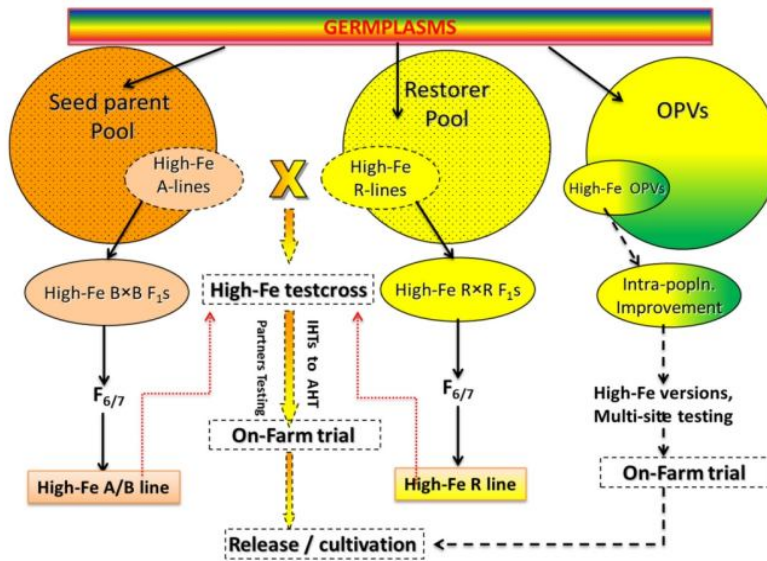
The pearl millet biofortification breeding program at ICRISAT has taken a three-pronged breeding phase-I, II and III. The first phase is a short-term strategy that focuses on trait genetics, germplasm screening, and genetic variability creation. The second phase is a medium-term strategy that involves confirming high-iron and zinc breeding lines and hybrid parents from the standard breeding programme in order to generate biofortified varieties/hybrids quickly. Long-term goal creation of high-Fe/Zn breeding lines and hybrid parents, as well as genetic diversification through steady mainstreaming micronutrient characteristics at ICRISAT and NARS breeding programmes, comprised the third phase, additive genes govern these micronutrients, and therefore biofortification breeding procedures are the same as for any other quantitative characteristic. Previous research has also suggested that additive gene activity is more important for grain Fe and Zn in pearl millet. Well defined the pedigree breeding approach, which is the most frequent method in pearl millet breeding and deals exclusively with progenies resulting from bi-parental crossings.

Composites are also used as a base population in this strategy, which has the potential to expedite genetic advances in hybrid yield and broaden the genetic basis of hybrid parents and cultivars. Composites, on the other hand, will only be used for hybrid parent pedigree breeding if they have all of the requisite characteristics. Different cytoplasmic sterility systems (CMS) exist in pearl millet, however, A1, A4, and A5 are the most extensively utilised. The typical three-line approach (A, B, and R) to make a hybrid seed includes the adoption of cytoplasmic genetic male sterility. A1 and A4 are currently utilised in commercial breeding projects in India. The A1 CMS is used in all pearl millet hybrids developed in India so far, while the biofortification effort uses.

The pearl millet biofortification process is currently moving from fast-track breeding to genetic diversification and mainstreaming the development of biofortified fast-track hybrids/varieties at ICRISAT. ICRISAT has proved the use of traditional breeding methods to combine micronutrients and grain yield. Despite high Fe levels, breeding parental lines (seed- and restorer-parents) with high Fe density as a target attribute will help achieve the long-term goal of hybridization. In this direction, 174 high-Fe early-generation progenies (BB progenies and RR progenies) have been produced, with > 90 mg kg<sup>-1</sup> Fe density and 36 to 72 mg kg<sup>-1</sup> Zn density in trials conducted at Patancheru. According to preliminary research, the identified

common and overlapping Quantitative Trait Loci (QTL) for Fe and Zn densities are in LG3 (chromosome 3) [21]. As a result, there is a lot of Fe and Zn variation in elite breeding populations, and additional research is needed in the future to develop diagnostic methods for screening segregating materials.

**Figure :1 Biofortification breeding approach:**



(Source: Govindarajet *al.*, 2019)

**Table: 2 Biofortified pearl millet hybrids or varieties:**

Sl. No	Name of the hybrid/variety	Year	Salient features	Yield (kg/ha)	Fe (ppm)	Zn (ppm)
1	DHANSHAKTI	2013	Early maturing variety, bold, globular, shining slate grey colour seed, cylindrical lanceolate earhead, resistant to downy mildew.	2199	81	43
2	HHB 229 (MH 2076)	2018	Medium maturing, purple anther colour, lanceolate shaped compact panicle, greyish hexagonal shape grain, resistant to major diseases and insect pests.	3274	73	41
3	AHB 1200 Fe (MH 2072) (AHB 1200)	2018	Medium maturing, long cylindrical panicle, resistant to downy mildew, stem borer, responsive to fertilizer.	3170	77	39
4	AHB 1269 Fe (MH 2185)	2019	Medium maturing, high Fe content.	3168	91	43
5	RHB 234 (MH 2174)	2019	Medium maturing, brown anther colour, complete exertion, greyish seed, resistant to major diseases and pests.	3169	84	41
6	RHB 233 (MH 2173)	2019	Medium maturing, yellow anther colour, complete exertion, greyish seed, resistant to major diseases and pests.	3157	83	46
7	HHB 311	2020	Medium maturing, compact panicle, grey coloured hexagonal shaped grains, highly resistant to downy mildew and other diseases.	3173	83	39

Source :Satyavathiet al., 2020b)

## **2. Micronutrient phenotyping using a high throughput method**

The precise phenotyping efficiency of high throughput instruments is critical to the success of a breeding program. This is a critical necessity in biofortification research, since it allows for rapid identification of high-Fe/Zn lines from a wide pool of germplasm and gene pools. The destructive techniques of Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) are widely employed by researchers, and their results for grain Fe and Zn densities are repeatable. However, breeding for micronutrient dense cultivars necessitates the screening of a large amount of genetic material, such as germplasm collections, elite lines, segregating populations, hybrids, and so on; and phenotyping for micronutrients using destructive techniques requires a significant amount of analytical time and breeding resources. An innovative approach was used in a recent study.

## **3. Genetic variability for micronutrients**

To begin any trait-specific breeding, breeders must have a lot of genetic variability. Thousands of pearl millet samples were examined for grain Fe and Zn density using the high throughput screening facilities. This is largely due to ICRISAT's efforts to scale the genetic variability available for these two micronutrients in working germplasm and breeding materials. ICRISAT researchers discovered a wide range of variability in grain Fe and Zn densities in a variety of breeding materials, including In iari germplasm accessions (51–121 mg/kg Fe; 46–87 mg/kg Zn), population progenies (18.0–135.0 mg/kg Fe; 22.0–92.0 mg/kg Zn), inbred parents (30.3–102.0 mg/kg Fe; 27.4 mg to 84.0 mg/kg Zn),

## **4. Breeding for genetic improvement**

### **a. Improving the nutritional characteristics of grain**

Because pearl millet is a highly nutritious cereal with higher levels of proteins and numerous minerals than other main cereals, the focus of core breeding has been to maximize production potential. According to previous study, germplasm can include up to 24.3 percent protein (Jambunathan and Subramanian, 1988) and elite breeding lines can contain up to 19.8 percent

protein (Jambunathan and Subramanian, 1988). However, because of the unfavourable associations between protein content and grain output, no substantial efforts were undertaken to improve it. In light of global identification of severe inadequacies of iron (Fe) and zinc, improving grain nutritional characteristics is a recent addition to breeding objectives (Zn). The scope of genetic variation for grain Fe and Zn contents, the identification of diverse seed-mineral dense germplasm, the nature of genotype-environment interaction, relationships between grain minerals and agronomic traits, and genetic control of micronutrients are among the major topics covered ( Govindarajet *al.*, 2019).

#### **b. Continuous replacement of hybrids**

In order to achieve continual genetic improvements, it is necessary to replace existing hybrids with new ones that have higher potential productivity.

Due to the widespread use of high-yielding and disease-resistant cultivars combined with improved production techniques, pearl millet productivity grew by more than 300 percent from 303 kg/ha in 1950–1954 to 1,239 kg/ha in 2015–2019.

#### **c. Genomics-Assisted Breeding**

One of the most exciting developments that have implications on taking the genetic gains to the next levels in pearl millet is genomics and genomics-assisted breeding that can help improve the precision and efficiency of the breeding program. The ~1,000 genomes sequencing project has been a major milestone in pearl millet improvement (Varshney *et al.*, 2017). This work has created a good framework for finding, mapping, and deploying QTLs/alleles/candidate genes connected to economically important traits.

#### **d. Precision Phenotyping**

While genotyping has become significantly cheaper and more precise in recent years, precision phenotyping has remained a significant problem, particularly in the case of drought. Only when rapid, reliable, and cost-effective phenotypic data, including root systems, is accessible for genetic dissection of drought tolerance and selection of drought-resilient genotypes, can genomic resources be fully utilized (Tuberosa, 2012).

#### **e. Heterotic Grouping of Hybrid Parental Lines**

Heterotic grouping of hybrid parental lines is an important strategy to increase the magnitude of heterosis on a long-term basis (Melchinger and Gumber, 1998). Depending on their individual phenotypic features, a varied range of breeding material has historically been utilised to generate either seed parents (B lines) or restorer parents (R lines) (Rai et al., 2006).

**f. Taking on both host resistance and pathogen variability at the same time**

The experience, so far, in resistance breeding for DM has indicated that most of the hybrids become susceptible in about 5–6 years of cultivation in the same area because of selection pressure in the pathogen, although there are some clear exceptions where hybrids have shown durable resistance. It would be useful to investigate resistance mechanisms operative in the parents of such hybrids to identify and deploy genes for durable Downey Mildew resistance in high-yielding hybrids for enhanced genetic gain.

**g. Hybrid Breeding for arid climates needs to be improved**

One of the key issues, often debated in past, has been the comparative advantage of hybrids or Open-pollinated varieties (OPVs) under severe drought conditions, given the reports that genetically heterogeneous to provide steady performance in unexpected drought settings, OPVs may use population buffering mechanisms (Bradshaw, 1965; Haussmann et al., 2000).

**h. Bringing biofortification into the mainstream**

To ensure nutritional security in SA and SSA, Fe and Zn should be mainstreamed in pearl millet breeding. Breeding for micronutrients and vitamins has been initiated by Harvest Plus, a CGIAR Challenge Program. In collaboration with national partners, ICRISAT has generated now enough database for Fe and Zn. As part of the ICRISAT product profile, Fe levels more than 60 ppm and Zn levels greater than 40 ppm were sought for breeding. This is a significant step forward in top breeding lines' mainstreaming.

**i. Enhancing nutrient use efficiency**

Although pearl millet is mostly grown on sandy and sandy-loam soils with low nitrogen (N) and phosphorus (P) content, its adaptation to low nutrients is rarely addressed, with the assumption that this problem can be readily solved by applying fertilizers.

**j. Collaboration of breeding and agronomics**

To achieve greater genetic gains, a sustained increase in pearl millet productivity requires the integration of appropriate cultural practices in its diverse production environments for disease-resistant and improved cultivars.

#### **k. Speed Breeding and Big-Data Analytics**

Genetic gains of any breeding program significantly depend upon the number of crop breeding cycles a program can undertake in a year. This changes depending on the local weather conditions in different breeding operations. In north India, for example, only one crop of pearl millet can be harvested per year, but western, central, and peninsular India can harvest two crops per year. In the current climate, breeding a new crop cultivar takes a decade or more, with 6 or 7 years spent on seasonal generational developments to arrive at elite materials ready for testing and distribution. Now, new environmentally controlled facilities, known as “Rapid Gen,” have been developed, which will shorten the 6–7-year window significantly. When used with the full suite of breeding acceleration techniques, Rapid Gen can make it possible to take four crop cycles in a year. (<https://www.icrisat.org/first-public-research-facility-to-put-agriculture-on-fast-forward-launched-at-icrisat/>).

#### **Future Prospectus**

In the semiarid and arid ecologies of South Asia (SA) and Sub-Saharan Africa (SSA), pearl millet (*Pennisetum glaucum* R. Br.) is an important crop (SSA), which is characterized by low and unpredictable rainfall, high mean temperature, and low organic carbon and water-holding capacity soils (Serbaet *al.*, 2020). Aside from its unrivalled drought tolerance, pearl millet has a built-in adaptation to low-fertility soils. Because of its remarkable ability to respond to favourable environments due to its short developmental stages, high photosynthetic efficiency, and abundant capacity for high growth rate, pearl millet is emerging as an important alternative crop for feed, food, fodder, and relay crop in Brazil, Canada, Mexico, the United States, West Asia, and North Africa (Yadav and Rai, 2013). During the previous six decades, India has made enormous progress in increasing productivity by introducing high-yielding cultivars and improving agronomic management. The accomplishments of pearl millet breeding are often referred to as one of the greatest success stories in Indian agriculture (Yadav *et al.*, 2019). However, the biological potential of pearl millet has not been fully realised, as seen by the

current national output of 1.2 tons/ha, which is lower than the summer season productivity of 4–5 tons/ha in northern India.

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