20 Biofortified Pearl Millet Cultivars Offer Potential Solution to Tackle Malnutrition in India

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Introduction

Dietary deficiency of micronutrients (iron, zinc, vitamin A), leading to micronutrient malnutrition or hidden hunger, has been recognized as a widespread food-related health problem, affecting more than 2 billion people worldwide (White and Broadley, 2009; Stein 2010; FAO, 2015; Darnton-Hill and Mkparu, 2015). This is primarily attributable to lack of affordability and access to diversified diet, such as fruits, vegetables and livestock products. As a consequence, women, children and infants, belonging to the poorer section of society are malnourished. In particular, deficiencies of iron and zinc are widespread, leading to numerous adverse health consequences, as they play a vital role in various physiological body functions.

India is a country historically plagued by malnutrition, where nearly 30% of people lie below the poverty line, with little dietary diversity, because of poverty and low purchasing power. Although government-supported programmes have shown a reduction in malnutrition across the decades, there has been slow progress, as National Family Health Survey-3 and National Family Health Survey-4 reported by IIPS and MI (2007) and IIPS and ICF (2017), respectively, revealed. In addition, there is an unacceptably high prevalence of anaemia, and underweight and stunted children under 5 years of age (Table 20.1). More than 50% of children and women in 20 states of India are reported to be anaemic (Fig. 20.1). This situation is further compounded because present diets are dominated by major fine cereals, such as rice and wheat, which are often low in micronutrients and are readily available in ready-to-cook forms through the Public Distribution System (PDS) at a subsidized price. The costs of these micronutrient deficiencies in preventable lives lost, poor quality of life and adverse health issues, as well as their impact on personal and national economic growth are huge, even in a country like India, which has commendable economic growth. Micronutrient deficiencies alone may cost India US$2.5 billion annually (Gragnolati *et al.*, 2005) and productivity loss of almost 3% GDP (Horton, 1999). Malnutrition, therefore, remains a serious problem in India, which is not only a consequence of poverty but also a cause of poverty (IFPRI, 2011).

Therefore, a multidisciplinary, sustainable and cost-effective approach, dubbed 'Biofortification –

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Table 20.1. Key indicators (in per cent) and magnitude of malnutrition in India over the years (IIPS and Macro International, 2007; IIPS and ICF, 2017).

Vulnerable group	NFHS-3 (2005–06)	NFHS-4 (2015–16)
Anaemia[a]		
Children (<5 years)	69.4	58.4
Non-pregnant women	55.2	53.1
Pregnant women	57.9	50.3
All women	55.3	53.0
All Men	24.2	22.7
Stunting		
Children	48.0	38.4
Women	NA[b]	NA
Men	NA	NA
Underweight		
Children	42.5	35.7
Women	35.5	22.9
Men	34.2	20.2

[a]Haemoglobin in grams per decilitre (g dl^{-1}).
[b]NA – not applicable.

breeding of staple crops for micronutrients', is ongoing both at global and national levels to bring together the potential of crop breeding and nutrition science to address hidden hunger. This effort is led by HarvestPlus – a CGIAR Challenge Programme convened by the International Food Policy Research Institute (IFPRI). In India, to start with, we chose to biofortify pearl millet (*Pennisetum glaucum* (L.) R. Br.), which is already known to be highly nutritious.

Why Biofortify Pearl Millet?

Pearl millet is grown in marginal arid and semi-arid tropical regions. India has the largest area in the world (8–9 million ha) and production (9–10 metric tonnes) (AICPMIP, 2016). It is cultivated on the sandiest, infertile soils, where other cereal crops fail to produce optimum yield. Being a dryland resilient crop and with high metabolizable energy, high protein content and balanced amino acid profile (Andrews and Kumar, 1992), pearl millet has a lot to offer. Low glycaemic index and gluten-free protein add special health benefits to pearl millet for those prone to diabetes and coeliac disease (Sehgal *et al.*, 2004; Dahlberg *et al.*, 2004). The consumption of pearl millet is higher in rural India, as compared to the urban population. This may be due to the fact that whole pearl millet grains are stored in villages, for up to 2 years, with few shelf-life challenges. However the shelf-life of pearl millet flour, as is stored by urban consumers, is short (10–12 days) because of rapid development of rancidity at ambient conditions (Satyavathi *et al.*, 2017). Nevertheless, pearl millet continues to be an important staple for the poor and low-income groups. Pearl millet as such is a high-iron crop with a fairly high zinc content. However, not all available cultivars have high iron and zinc content. For instance, nearly twofold variability (31–61 mg kg^{-1}) was observed for iron content and one-and-a-half-fold variability (32–54 mg kg^{-1}) for Zn content among 122 commercial and pipeline hybrids developed so far in India. The average level of iron in these commercial cultivars is 42 mg kg^{-1}; thus, there is a need to increase the Fe and Zn levels in this crop (Rai *et al.*, 2016). Remarkably, pearl millet has larger variability for iron and zinc content than do rice and wheat. For instance, pearl millet has 300% and 600% higher iron content than in wheat and rice, respectively (Passi and Jain, 2014). This indicates that pearl millet is a suitable target crop for iron biofortification. Unlike other crops, pearl millet foods are prepared using wholegrain flour and no significant losses occur in the total nutrient content during processing. Considering these adaptive and nutritional features, combined with high yield potential, pearl millet is an important cereal crop that can effectively address the emerging challenges of climate change, water scarcity for agriculture and food-related health issues, particularly iron-deficiency-induced anaemia. In addition, HarvestPlus developed the Biofortification Priority Index (BPI) to help stakeholders assess which country–crop combinations will have the greatest impact in reducing micronutrient deficiencies. The BPI ranks 128 countries according to their impact potential for investment in each of the eight biofortified staple food crops (Asare-Marfo *et al.*, 2013; https://bpi.harvestplus.org). India ranks first for intervention with iron-biofortified pearl millet under the population-weighted BPI and second under the area-weighted BPI (Fig. 20.2). Therefore, expanding pearl millet's role as a biofortified food in dryland systems is highly important in the research and development sectors.

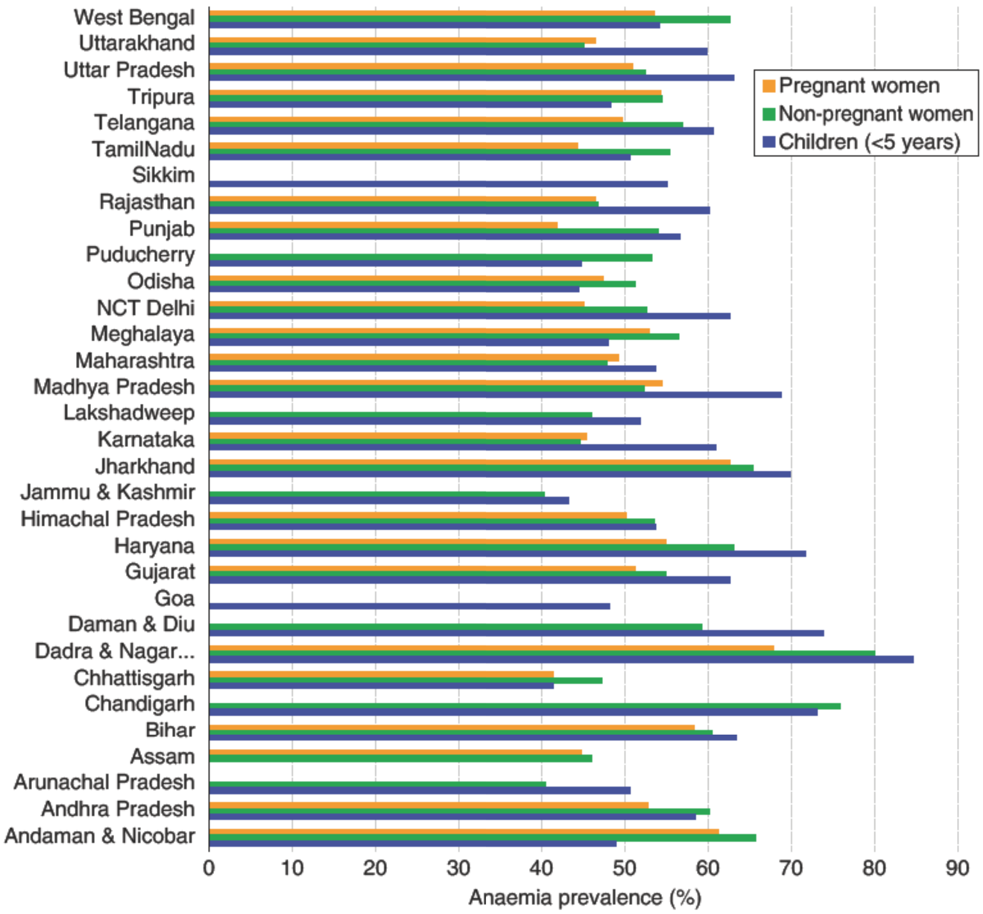

Fig. 20.1. High prevalence of anaemia (>40%) among vulnerable groups in different states across India. (IIPS and ICF, 2017.)

Breeding Target for Biofortified Pearl Millet

The primary target trait in pearl millet breeding is iron content, while zinc is an associated secondary trait. Nutritionists at HarvestPlus agreed that to detect measurable health impact, >30% of the estimated average requirement (EAR) should be achieved through biofortification. The baseline for iron for wholegrain pearl millet was found to be 47 mg kg^{-1} and an additional 30 mg kg^{-1} over the baseline was set as a breeding target (i.e. 77 mg kg^{-1}). These figures were arrived at on the basis of per capita consumption (220 g day^{-1} for adult women; 85 g day^{-1} for children 4–6 years of age), 7.5% bioavailability and 90% micronutrient retention after processing (Pfeiffer *et al.*, 2018).

On the other hand, the baseline for Fe was revisited using more extensive commercial hybrid trial data in India, to derive a baseline for hybrids that occupy more than 90% of the pearl millet area under improved cultivars in India. In an extensive study, Rai *et al.* (2016) suggested a baseline of 42 mg kg^{-1} in hybrids, hence the revised target level of iron for hybrids is set at 72 mg kg^{-1}. It is interesting to note that all the high-Fe cultivars (both open-pollinated varieties [OPVs] and hybrids) identified in this study have ≥35 mg kg^{-1} of Zn density, which is on a par with the target level determined for biofortified high-Zn wheat varieties (Velu *et al.*, 2012).

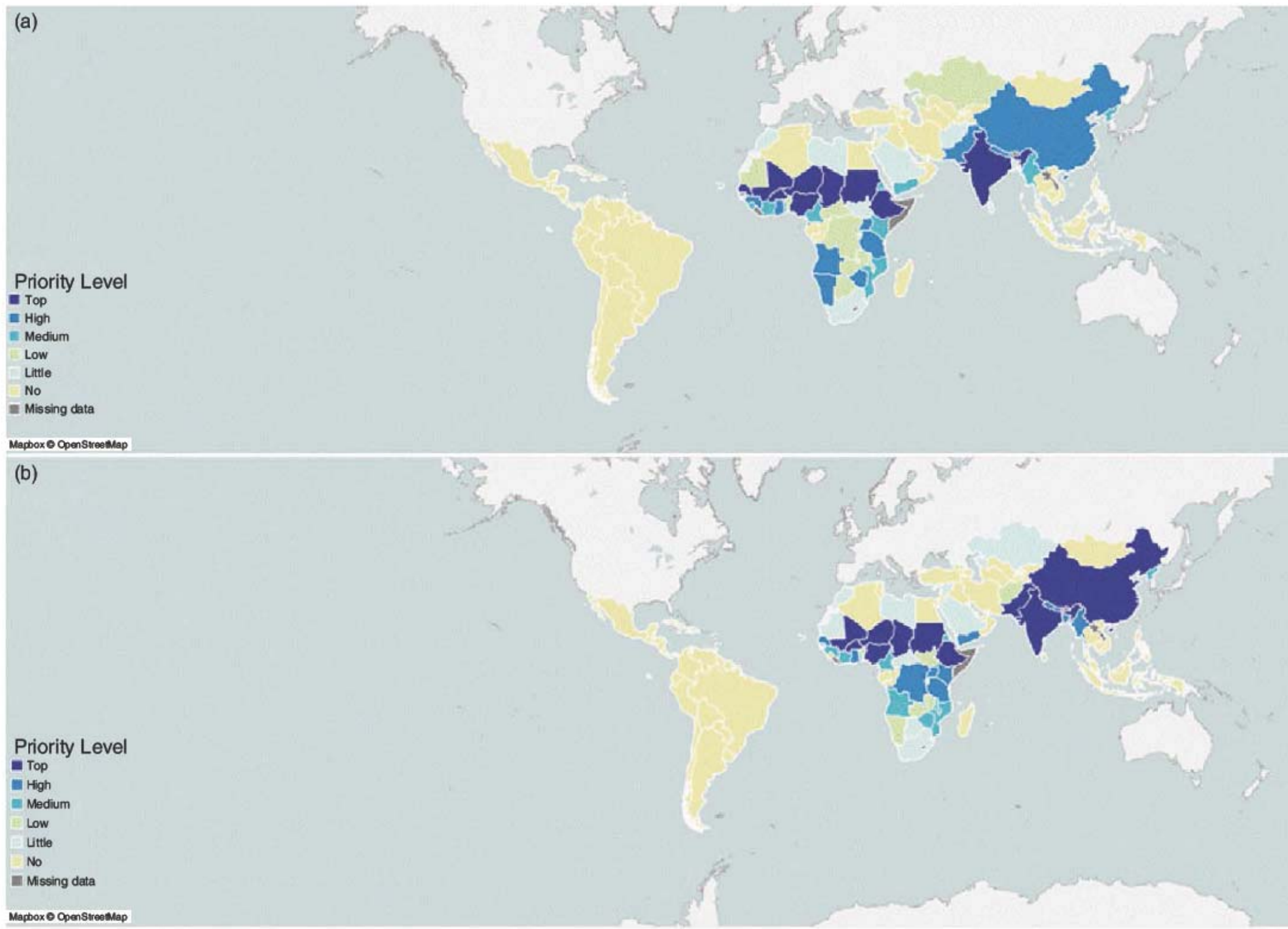

Fig. 20.2. Biofortification priority index indicating significance of breeding iron pearl millet. (a) Priority countries based on population weighted; (b) priority countries based on land area weighted.

Improved Phenotyping Protocol

For the success of a breeding programme, high-throughput, cost-effective phenotyping is a prerequisite. Initially, phenotyping was possible with the support from a well-established analytical laboratory facility at ICRISAT, which does high precision analysis following atomic absorption spectrometer (AAS) and inductively coupled plasma (ICP) procedures. However, these methods are very expensive and offer very low throughput. Hence, there was a need to develop a cost-effective and high-throughput screening procedure to speed up the breeding and product development process. The X-ray fluorescence (XRF) spectrometry calibrations and standards were developed for high-throughput screening in pearl millet (Paltridge *et al.*, 2012). The XRF method is low-cost, non-destructive, needs a small quantity of sample and has the ability to screen >300 samples per day (Rai *et al.*, 2012; Govindaraj *et al.*, 2016a). As pearl millet is a cross-pollinated crop, three types of seed samples (selfed, sibbed and open-pollinated [OP]) can be used for mineral analysis. The differences for iron and zinc among these types of grain samples were not significant (Rai *et al.*, 2015a), suggesting that the utilization of OP seed is the most cost-effective method of estimating Fe and Zn density. Research on genetic enhancement of grain iron and zinc content in pearl millet at ICRISAT has made significant progress in assessing the variability for these micronutrients in germplasm accessions and breeding lines using the above protocols.

Cultivar Development Strategy

In India, pearl millet OPVs were the dominant cultivars in the past (still occupying ≈ 30% area). However, now hybrids are cultivated on more than 5 million ha. The biofortification breeding at ICRISAT has assumed full operational scale and breeding pipeline, including OPVs, hybrids and hybrid-parent development. Both the public and private sectors are actively engaged in breeding pearl millet hybrids. This initiative is supported by ICRISAT through the Pearl Millet Hybrid Parent Research Consortium (PMHPRC).

The extent of genetic variation is very critical to initiate a breeding programme aimed at trait-specific breeding. The assessment of micronutrient variation was undertaken using phenotyping protocols, as described earlier. Pearl millet showed large genetic variability for both Fe and Zn densities in advanced breeding lines, populations and germplasm (Govindaraj *et al.*, 2015; Table 20.2), indicating good prospects for their genetic enhancement. As these traits were governed by additive gene action and their heritabilities were relatively high (Velu *et al.*, 2011; Govindaraj *et al.*, 2013; Kanatti *et al.*, 2014; Govindaraj *et al.*, 2016b), the pedigree method of breeding was deployed for progenies derived from primarily biparental crosses, as described by Andrews *et al.* (1996). It also meant that hybrid parental lines should be bred separately for high micronutrient density, requiring a separate hybrid parent-development programme.

Table 20.2. Variability for iron (Fe) and zinc (Zn) densities in pearl millet at ICRISAT, Patancheru. (Govindaraj *et al.*, 2015.)

Material	Entry	Per cent entry in micronutrient class (mg kg^{-1})							
		Fe density							
		≤45	46–55	56–65	66–75	76–85	86–95	96–105	>105
Mainstream hybrid parents	290	24	31	18	10	7	7	3	1
Commercial cultivars	140	56	35	9	1	0	0	0	0
Germplasm accessions	406	11	19	16	19	17	12	5	1
Biofortified breeding lines	514	0	0	0	2	11	22	27	38
		Zn density							
		≤35	36–45	46–55	56–65	66–75	76–85	86–95	>95
Mainstream hybrid parents	290	5	47	34	11	2	0	0	0
Commercial cultivars	140	8	76	16	0	0	0	0	0
Germplasm accessions	406	2	16	31	32	17	2	0	0
Biofortified breeding lines	514	8	45	40	7	0	0	0	0

Almost all iron sources identified are based on *iniadi* germplasm (early-maturing, large-seeded landrace materials from a geographic area adjoining Togo, Ghana, Burkina Faso and Benin) or have a large proportion of *iniadi* germplasm in their parentage (Rai *et al.*, 2015b). Hence, *iniadi* is a valuable germplasm resource for genetic improvement of micronutrients in pearl millet. Highly significant and positive correlations between iron and zinc content indicated good prospects for simultaneous selection for both micronutrients. Both micronutrients, in general, have been found not to be correlated with 1000-grain weight and flowering time, indicating that pearl millet cultivars with high Fe and Zn densities can be effectively bred with large grain size and in a range of maturity classes for different agroecological regions (Rai *et al.*, 2014; Govindaraj *et al.*, 2019). The major focus of the breeding programme is to develop higher yielding, high-iron hybrids with stable yield and enhanced iron, for the different agro-ecological zones in India. Major traits in delivering final biofortified products include resistance to diseases, such as downy mildew and blast, drought tolerance and fodder yield.

Current Status and Future Prospects for Biofortified Pearl Millet Cultivars

ICRISAT, in association with national partners, developed and identified a high-iron variety 'Dhanashakti' that had the highest level of iron content among all pearl millet cultivars produced so far. Dhanashakti was initially targeted for Maharashtra state, but it also performed equally well in other states of central and southern India and was released by Mahatma Phule Krishi Vidyapeeth for cultivation in all pearl millet-growing states of India in 2014 (Rai *et al.*, 2014). It was developed by an intra-population improvement of ICTP 8203 that was released in 1990. Dhanashakti has 9% higher iron and 11% higher yield than ICTP 8203. ICMV 221, another popular OPV variety, is also under improvement for iron (Govindaraj *et al.*, 2019).

Two hybrids (ICMH 1202 and ICMH 1203) were released in 2017 and notified by the All India Coordinated Millet Improvement Project (AICPMIP) in 2018. In 2018, five more hybrids, namely AHB 1269, HHB 311, RHB 233, RHB 234 and ICMH1301, were released in India (Table 20.3). Currently, five hybrids, namely GHB 1225, PBH 1625, AHB 1382, ICMH 1601 and RHB 257, are in various stages of evaluation in the AICPMIP or state trials.

The seeds of Dhanashakti had been produced and marketed by HarvestPlus partners, namely Nirmal Seeds, Maharashtra State Seed Corporation and Karnataka State Seed Corporation. The commercial production of ICMH 1201 was undertaken by Shaktivardhak Seed Company under the brand name 'Shakti-1201' and 13 metric tonnes of Truthfully Labelled Seed (TLS) was sold in the states of Maharashtra and Rajasthan (Purushottam Singh *et al.*, 2016). Adoption of recently released hybrids is likely to take place in the near future. Overall, >93,000 households in four states (Maharashtra, Rajasthan, Uttar Pradesh and Haryana) have access to biofortified pearl

Table 20.3. Performance and some salient features of released biofortified pearl millet cultivars in India

Hybrid	Release year	Grain colour	Grain size	Yield potential (t ha^{-1})[a]	Iron density (mg kg^{-1})[b]
Dhanashakti	2014	Dark grey	Bold	2.0	71
ICMH 1202 (AHB1200Fe)	2017	Grey	Bold	3.5	70
ICMH 1203 (HHB 299)	2017	Grey	Bold	3.2	67
ICMH 1301 (DHBH1211)	2018	Grey	Bold	3.3	78
ICMH 1501 (HHB 311)	2018	Grey	Medium	3.5	60
ICMH 1502 (AHB1269)	2018	Grey	Bold	3.2	73
ICMH 1503 (RHB 233)	2018	Grey	Bold	3.2	65
ICMH 1504 (RHB 234)	2018	Grey	Medium	3.2	60

[a]Mean data from AICRP-PM test locations.
[b]XRF data.

millet since the first biofortified variety was released in India (Binu Cherian, HarvestPlus-ICRISAT, 2019; personal communication).

Seven hybrids released so far represent the first wave of hybrids that were developed in collaboration with national partners. These hybrids possess >70% of the iron target increments and about 10–20% lower grain yield than the highest yielding commercial hybrid check (Fig. 20.3, Table 20.3). This is primarily attributable to the fact that all the high-Fe pearl millet hybrids released so far were developed using pre-existing medium- to high-Fe seed parents and advanced high-Fe breeding lines as potential restorers. These materials were not purposely bred for high yield and Fe and Zn density as target traits in the mainstream breeding programme. Consequently, yield levels of the first wave of biofortified hybrids are not as high as those of commercial high-yielding checks (Govindaraj *et al*., 2019).

However, the next wave of biofortified hybrids are being bred through directed breeding for high yield, along with high-Fe/Zn (Figure 20.4). In addition, to fulfill the long-term objective and continued supplies of breeding material, at ICRSIAT, we continue to mainstream breeding for iron and zinc, along with other core traits. The next generation of biofortified parental lines (with disease resistance) are being developed. The current breeding strategy ensures that the crosses include at least one parent having high iron content (>60 mg kg^{-1}) to enable mainstreaming of the iron trait in the next few years in a sustainable manner, as committed by the CGIAR Consortium and its member institutes at the Second Global Conference on Biofortification in Kigali, Rwanda. To this effect, promising lines have been identified with >80 mg kg^{-1} Fe density and 40–60 mg kg^{-1} Zn density and are being used in developing the next generation of seed-parents and restorer lines to develop the next generation of high-yielding and high-Fe hybrids. About 30 seed-parents (A/B pairs), purposely bred for high-Fe (70–110 mg kg^{-1}), have been designated with disease resistance in three diverse cytoplasm sources ($A_1/A_4/A_5$). Similarly, about 30 high-Fe restorers have also been identified and designated. Seeds of these designated parents are being multiplied for sharing with collaborators and will serve as potential parents of the future biofortified hybrids. We believe that this targeted

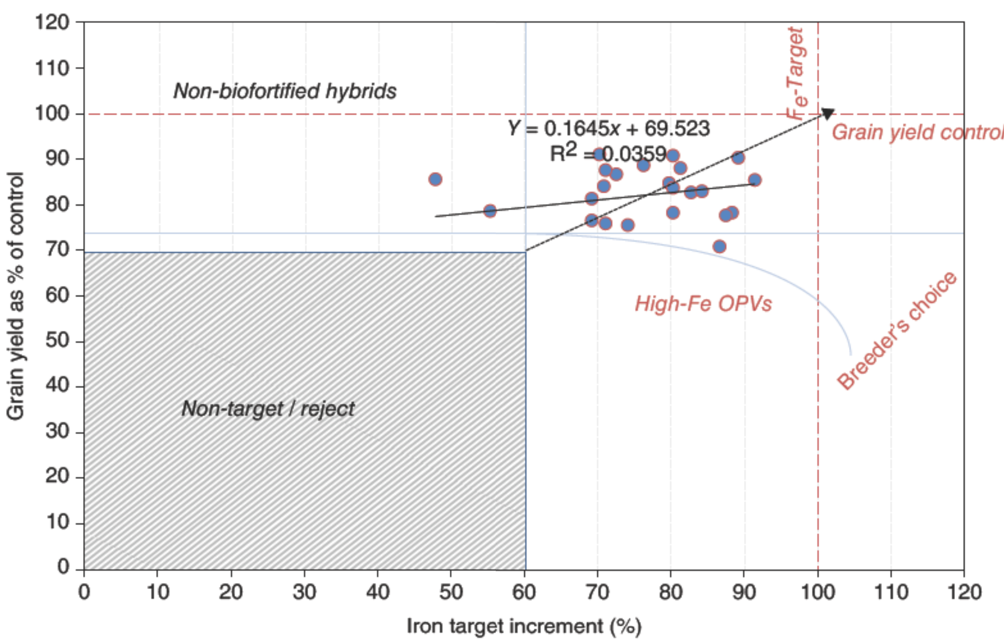

Fig. 20.3. Current biofortification breeding progress on hybrid development towards the target increments for yield and iron content (data from 2012 trials). OPV, open-pollinated variety.

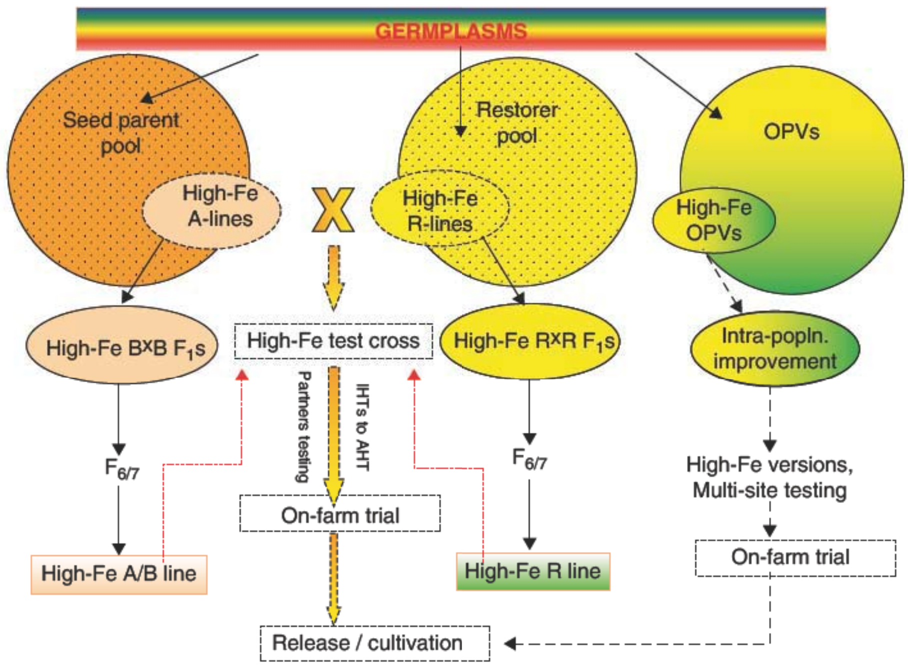

Fig. 20.4. Current fast-track biofortification breeding strategy (dotted lines) followed at ICRISAT. (Adapted from Govindaraj *et al.*, 2019.) OPV, open-pollinated variety; IHTs, Initial hybrid trial(s); AHT, advanced hybrid trial.

breeding approach will result in the production of a second generation of biofortified hybrids with competitive yield potential comparable to or surpassing the commercial hybrids.

Biofortified Cultivar Release Policy

The Indian Council of Agricultural Research (ICAR) and AICPMIP have been very supportive of biofortification of pearl millet. As early as 2015, AICPMIP constructed a special module to test and release biofortified pearl millet cultivars in India. Furthermore, ICAR has endorsed the inclusion of the minimum levels of iron and zinc for future pearl millet varieties to be released in the country. AICPMIP in 2018 decided on a minimum of 42 mg kg^{-1} of iron and 32 mg kg^{-1} of zinc (AICRP-PM, 2017) (https://www.icrisat.org/committed-to-alleviating-malnutrition-india-declares-minimum-levels-for-iron-and-zinc-in-pearl-millet/). These mandatory initiatives should help mainstream biofortified traits in various national breeding programmes in India.

Nutritional Bioavailability and Efficacy Evidence

To demonstrate that the micronutrients bred into pearl millet or any other cereal are bioavailable and have measurable impact on micronutrient status and functional indicators of micronutrient status, such as physical activity and cognition tests, nutritionists conduct randomized, controlled efficacy trials. This evidence is necessary to convince all stakeholders, especially policy makers of the benefits of biofortified foods.

A set of efficacy studies was conducted (Kodkany *et al.*, 2013; Pompano *et al.*, 2013; Scott *et al.*, 2014; Tako *et al.*, 2015; Finkelstein *et al.*, 2015, 2017, 2019; Jen Foley, 2019, Vancouver, personal communication). Research findings from these studies are briefly presented below.

- Pearl millet biofortified with iron can provide young children with 100% of their daily iron needs. When eaten as the main part of the diet, it reverses iron deficiency and improves the health of adolescent Indian children.

  - In rural Maharashtra, when secondary school children ate biofortified *bhakri* twice a day and snacks at will for 6 months, iron deficiency was significantly reduced.
  - Even after only 4 months, iron levels were significantly improved in all children eating iron pearl millet.
  - Notably, the impact of the additional dietary iron was greatest in those who needed it the most. Children with iron deficiency at the start of the study were 64% more likely to have their deficiency reversed after 6 months if they ate iron pearl millet instead of traditional millet.
- Eating iron pearl millet also improves cognitive performance, including memory and attention – skills essential for reaching one's full potential at school and work.
- Significant positive and protective effects from iron-biofortified crops, including iron pearl millet, have been proven across continents and populations, particularly among women and children in poor communities.
- In addition to increasing iron, biofortification increases zinc in pearl millet to levels that can meet the daily needs of young children. This is beneficial because iron, zinc and other micronutrient deficiencies often co-exist in the Indian population.

The iron-nutrition research presented above has demonstrated beyond doubt the efficacy of biofortified pearl millet in improving the nutritional status of target populations. Therefore, pearl millet biofortification offers a sustainable solution to iron and zinc deficiencies among millet-growing and millet-consuming populations and then can penetrate into non-millet growing but millet-consuming urban-poor populations for improving their health.

The Way Forward to Eradicate Malnutrition in India

Biofortification is one of the key approaches, which is cost-effective and sustainable to address global hidden hunger in the world, including India. The recent 'National Nutrition Strategy' by NITI Aayog, Government of India, would provide impetus to utilize biofortified varieties more effectively towards achieving 'Kuposhan Mukt Bharat' ('malnutrition-free India'). A framework has been suggested in the 'Vision 2022' for National Actions to eradicate malnutrition (Singh, 2019). The Integrated Child Development Service (ICDS) scheme – the world's largest nutrition programme, was launched in India in 1975 to address the health and nutrition needs of children under 6 years of age, which can be used as a vehicle to promote biofortified foods. Other initiatives, such as a Public Distribution System (PDS), Mid-Day Meal Scheme (MDMS) and the Food Bill, Food – a legal right, 2013, etc. are also in place to address micronutrient malnutrition. Innovative policy interventions, such as preferential seed subsidy and price incentives to grain producers and, would trigger adoption of iron pearl millet and other biofortified crops.

Summary and Conclusions

One-third of the global population suffers from one or more micronutrient deficiencies. More than 50% of children and women in 20 states of India are anaemic. Most of the suffering populations get their calories from main staple crops. Biofortification is the process of breeding micronutrient traits into staple food crops, which are bioavailable. It has been proven that biofortified crops have a positive and measurable impact on the health of consuming populations. Biofortification is a cost-effective and sustainable strategy and it complements the existing interventions, such as commercial food fortification and supplementation. However, biofortification has the potential to reach malnourished populations in relatively remote rural areas where other approaches have had little impact. Pearl millet, known to be highly nutritious, is the most important drought- and climate-resilient cereal crop, widely grown in Asia (9 million ha). It is a nutritious dryland crop having high protein, micronutrients and a more balanced amino acid profile than other staple cereals. In 2018, the Government of India, renamed millets, including pearl millet, as Nutri-Cereals. The average level of iron and zinc in the commercial pearl millet cultivars is 42 mg kg^{-1} and 32 mg kg^{-1}, respectively. However, the large extent of genetic variability for these traits (Fe 30–140 mg kg^{-1}, Zn 20–90 mg kg^{-1}) encouraged plant breeders to improve their content in pearl millet. HarvestPlus and ICRISAT collaborated to address the Fe and Zn deficiencies through biofortification of pearl millet. However, the principal emphasis of pearl millet biofortification is on improving primarily grain Fe. A decade of research and development on high-iron breeding pipelines and release of eight biofortified pearl millet cultivars led to the cultivation of biofortified pearl millet varieties on ~75,000 ha in India, reaching >93,000 households. To scale up, investment commitment in crop breeding, both in the public and private sector, and favourable policies, such as seed subsidy, price incentives for grain producers and integration of biofortified varieties into the existing Public Distribution and Mid-Day Meal Schemes, are warranted.

Biofortification is an evidence-based, sustainable and cost-effective approach to address malnutrition through the development, release and adoption of yield-competitive varieties possessing additional micronutrient content (Bouis and Saltzman, 2017). Biofortification helps reach relatively remote rural populations, who have limited access to commercially marketed fortified foods. We recognize that biofortification and commercial fortification are complementary strategies. However, biofortification is particularly advantageous where households consume large amounts of food staples that are often poor in micronutrients, and are most vulnerable to hidden hunger (Bouis, 2000; Bouis *et al*., 2011). It has been shown that farmers have adopted both OPVs and hybrid varieties of pearl millet with higher iron content. However, we need to work with all stakeholders in the full value chain to maximize impact with a mindset of 'farm to fork' rather than just development and release of biofortified varieties. Hence, to scale up and strengthen the breeding pipeline and uptake of these varieties, public and private partners need to work together at national and international levels. Agriculture investments and favourable policies to promote biofortification will enhance the availability of nutritious food to farmers and communities. Linking biofortification to the ongoing government initiatives, such as inclusion of biofortified pearl millet in the Public Distribution System and Mid-Day Meal Schemes to address malnutrition, would trigger demand. Increased demand for biofortified food would create market opportunities for farmers, thereby boosting their income. Pearl millet has the potential to make significant contributions to food and nutritional security in semi-arid regions of India.

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