Towards nutrition security of India with biofortified cereal varieties

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Rice and wheat are the major staples contributing more than 75% to food-grain consumption, while maize, pearl millet and sorghum are important alternative cereals in India. Cereal biofortification is one of the promising approaches to alleviate micronutrient malnutrition. Here we present an overview of the efforts towards development of biofortified cereal varieties enhanced with iron, zinc, protein and provitamin-A using conventional breeding approaches, and the possibilities of scaling up and adoption to ease the burden of malnutrition.

Keywords: Biofortification, breeding, cereals, micronutrient malnutrition, nutrition security.

DEFICIENCIES of vitamins or minerals result in micronutrients malnutrition, often called hidden hunger as the symptoms are not apparent like protein-energy malnutrition. The Comprehensive National Nutritional Survey (CNNS) of India conducted on around one lakh children during 2016–18 revealed incidences of anaemia, zinc (Zn) and vitamin deficiencies.

The Government of India (GoI) implements multiple programmes to address micronutrient malnutrition such as National Nutrition Mission (POSHAN Abhiyaan), prophylactic supplementation of vitamin A, iron (Fe) and folic acid, and fortification of wheat flour, table salt and milk with vital micronutrients. A special emphasis on complete fortification of rice in the public distribution system (PDS) by 2024 has also been recently mooted by GoI.

The Indian Council of Agricultural Research (ICAR), New Delhi is playing a major role in ensuring food security for the nation by providing the research thrust for production of food grains (www.icar.org.in). Realizing the necessity of better nutrition in food grains, ICAR started several special programmes on development and popularization of biofortified crops and more than four million hectares is estimated to be under cultivation of biofortified crops in India. The present review summarizes the efforts...
of ICAR in the development and release of biofortified cereal varieties, case studies of efficacy and scaling-up of biofortified varieties across the world, and policy implications for integration of biofortified cereal varieties in the country.

Identification of donor lines for high nutrient content

The primary criterion for the development of nutrient-rich or biofortified varieties is the availability of genetic variability for traits of interest in the germplasm. Using donors from the germplasm such as wild species, landraces and different genomes as in wheat, biofortified cereal varieties with enhanced nutrients can be developed deploying conventional breeding or marker-assisted selection (MAS) methods. For example, wide genetic variability exists for Zn and protein in polished rice. For Fe, though wide genetic variability exists in brown rice, the content is reduced drastically while polishing (milling) the rice. Conventional maize has inferior endosperm protein composition because of low essential amino acids content such as lysine and tryptophan. The discovery of maize mutant opaque2 (o2) with enhanced levels of essential amino acids resulted in the development of diverse, open-pollinated varieties and hybrids in quality protein maize (QPM) background. Natural genetic variation in β-carotene hydroxylase 1 (crtRB1) gene is now used as a source for the development of provitamin-A-rich maize through MAS. In wheat, wide genetic variability exists for Fe, Zn and protein, and in pearl millet and sorghum large genetic variability for Fe and Zn has been reported, which can be exploited for breeding of biofortified varieties. Simultaneously, anti-nutritional factors affecting the bioavailability of minerals like phytates are also being characterized during the development of biofortified cereals.

Development of biofortified cereal varieties

For acceptance and adoption by farmers, biofortified varieties should be high-yielding with the desirable quality parameters. Since most of the donor genotypes for nutrient traits are poor yielders, conscious breeding efforts are needed to combine high yield and high nutrient content while developing biofortified cereal varieties. For the phenotyping of biofortified genetic material, a high-throughput estimation system like X-ray fluorescence spectroscopy (XRF) is needed for quick identification of promising lines from breeding materials with increased nutrient content. The HarvestPlus initiative provided XRF equipment to several national and international laboratories in India to facilitate rapid estimation of Fe and Zn. In addition to the strong and active conventional breeding programmes, biotechnological strategies like MAS are also being deployed in the development of biofortified cereals, e.g. maize and wheat.

Evaluation and release of biofortified cereal varieties

ICAR adopts systematic evaluation of breeding materials of various crops through All India Coordinated Research Project (AICRP) networks across the country to identify consistent genotypes for yield along with other traits for the commercial release of varieties (https://www.icar.org.in/content/aicrps-network-projects). This approach based on multi-location testing facilitates rapid generation of breeding lines by developers and identification of appropriate high-yielding varieties, which are then notified as new varieties by the Central Sub-Committee on Crop Standards, Notification and Release of Varieties (CSCCSNRV) for commercial cultivation. The biofortified cereal breeding lines are being evaluated under AICRP through a separate biofortified trial in rice (http://www.aicrip-intranet.in/), integrated with quality trials in wheat (https://www.iiumr.icar.gov.in). For pearl millet, minimum Fe and Zn content was made mandatory for varietal release in India. Since 2013, several biofortified cereal varieties have been released by ICAR through evaluation under AICRP. In addition to facilitating the release of biofortified varieties, various initiatives of ICAR for the development and release of biofortified cereals through the National Agricultural Research System (NARS) along with international institutions and private organizations to achieve nutritional security of the nation are summarized in this review.

Rice

Rice is the major staple for two-thirds of the Indian population. However, polished rice, the most preferred form for consumption is a poor source of nutrients. The baseline derived from Zn content in polished (milled) rice of popular varieties ranges from <12 to 14 mg kg⁻¹, and even up to 35 mg kg⁻¹ has been reported in the rice germplasm. The baseline of protein in polished grains of different varieties widely grown by the farmers is about 7–8% and the range of grain protein content in indica germplasm is more than 15% (refs 17, 18). Several donors in rice germplasm have been identified with high Zn and protein content, but ~40% of nutrients is lost during polishing. Conventional breeding efforts deploying the existing genetic variability could increase Zn and protein in polished rice leading to the release of nine biofortified rice varieties through the All India Coordinated Rice Improvement Project (AICRIP) (Table 1). For the biofortified rice varieties to be released under AICRIP in India, either their Zn content should be 24 mg kg⁻¹ or their protein content should be ≥10% in polished rice; the yield should be on par with...
yield-check genotype along with the desired cooking quality.

**Wheat**

Wheat is another major staple food crop in addressing food security of India. The baseline of nutrients in adapted varieties of wheat is about 32–35 mg kg$^{-1}$ of Fe, 30–32 mg kg$^{-1}$ of Zn and 10.5–11.5% of protein. The benchmark levels for nutrients were set as 45 mg kg$^{-1}$ of Fe, 40 mg kg$^{-1}$ of Zn and 13% of protein$^{13}$. Studies indicated wide variability in landraces and secondary gene pool, viz. two-fold variations in Fe and Zn content among hexaploid wheat genotypes and fourfold in diploid/durum/dicoccum accessions$^{9,19-21}$. A quantitative trait locus (QTL) ($Gpc-B1$) associated with higher protein content was identified in *Triticum dicoccoides*, and transferred into wheat for higher grain protein and mineral content in India$^{12}$. The introgression of resistance of stripe rust genes along with a combination of higher grain protein is also being attempted. Through the AICRP on Wheat and Barley, more than 25 biofortified varieties comprising both bread and durum wheat with either high Fe or Zn or protein, or their combinations, have been released in India (Table 2). In durum wheat, additional trait of yellow pigment content is also taken into consideration.

**Maize**

Maize can significantly alleviate malnutrition in India with its promising protein quality and provitamin-A, although it is not a major staple food in the country. Traditional maize contains low lysine (1.5–2.0%) and tryptophan (0.3–0.4%) in endosperm protein, while the target level is 3.5–4.0% lysine and 0.8–1.0% tryptophan$^{13}$. A recessive gene $o2$ enhances lysine and tryptophan by nearly two-fold$^{22}$. Since the release of the first soft endosperm-based nutritious maize composites in 1970, the first hard-endosperm QPM composite in the late 1990s and the first QPM hybrid in 2000s, several QPM hybrids have been released so far for commercial cultivation in various agro-ecologies of the country$^{23}$. Research efforts have also led the development of four QPM versions of elite commercial hybrids through MAS$^6$. Traditional yellow maize contains low levels of provitamin-A (<2.5 mg kg$^{-1}$) compared to the global target of 15 mg kg$^{-1}$ (ref. 8). Using the favourable allele of *crtRB1*, provitamin-A of parental lines was increased to 15 mg kg$^{-1}$ in freshly harvested grains. Provitamin-A-rich version of QPM hybrids have been developed through MAS (Table 3). Fourteen hybrids of maize which are rich in provitamin-A or with a combination of high lysine, tryptophan and provitamin-A have been released for commercial cultivation in India.

**Pearl millet**

Biofortified pearl millet is a success story in India with its first released variety ‘Dhanashakti’ for high Fe with the research programme supported by HarvestPlus, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru and AICRP on Pearl Millet. The benchmark levels for optimum Fe (>42 mg kg$^{-1}$) and Zn (>32 mg kg$^{-1}$) content were fixed for varietal release in pearl millet through AICRP, and several biofortified varieties have also been released$^{13}$ (Table 4). New sources of Fe and Zn content (other than *iniadi*) in the germplasm collection are also being explored for genetic diversification for high Fe and Zn content$^{24}$. The development of biofortified pearl millet hybrids/varieties invariably includes high yield, downy mildew resistance and drought tolerance required for ready adoption by the farmers.

**Sorghum**

Sorghum is an important staple crop for the resource-poor farmers in the drylands with its better resilience to adverse climatic conditions like heat and drought$^{25}$. Wide variability for grain Fe (12–68 mg kg$^{-1}$) and Zn (11–44 mg kg$^{-1}$) was

### Table 1. Released biofortified rice varieties with high zinc and protein

<table>
<thead>
<tr>
<th>Variety</th>
<th>Zinc (ppm)</th>
<th>Protein (%)</th>
<th>Year of release</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR Dhan 310</td>
<td>–</td>
<td>10.3</td>
<td>2016</td>
<td>ICAR-NRRI, Cuttack</td>
</tr>
<tr>
<td>DRR Dhan 45</td>
<td>22.6</td>
<td>–</td>
<td>2016</td>
<td>ICAR-IIRR, Hyderabad</td>
</tr>
<tr>
<td>DRR Dhan 48</td>
<td>24.0</td>
<td>–</td>
<td>2016</td>
<td>ICAR-IIRR, Hyderabad</td>
</tr>
<tr>
<td>DRR Dhan 49</td>
<td>25.2</td>
<td>–</td>
<td>2016</td>
<td>ICAR-IIRR, Hyderabad</td>
</tr>
<tr>
<td>Zinco Rice MS</td>
<td>27.4</td>
<td>–</td>
<td>2018</td>
<td>IGKV, Raipur</td>
</tr>
<tr>
<td>CR Dhan 311</td>
<td>20.1</td>
<td>10.3</td>
<td>2018</td>
<td>ICAR-NRRI, Cuttack</td>
</tr>
<tr>
<td>CR Dhan 315</td>
<td>24.9</td>
<td>–</td>
<td>2020</td>
<td>ICAR-NRRI, Cuttack</td>
</tr>
<tr>
<td>CR Dhan 411</td>
<td>–</td>
<td>10.1</td>
<td>2021</td>
<td>ICAR-NRRI, Cuttack</td>
</tr>
<tr>
<td>DRR Dhan 63</td>
<td>24.2</td>
<td>–</td>
<td>2021</td>
<td>ICAR-IIRR, Hyderabad</td>
</tr>
</tbody>
</table>

ICAR-NRRI, ICAR-National Rice Research Institute; ICAR-IIRR, ICAR-Indian Institute of Rice Research; IGKV, Indira Gandhi Krishi Vishwavidyalaya.
observed among the public-bred cultivars, parental lines and some selected germplasm accessions along with a positive correlation between grain Fe and Zn. Based on available variability and stability and the baseline content of Fe as 25–28 mg kg\(^{-1}\) and Zn as 15–18 mg kg\(^{-1}\), the benchmark levels are being proposed for varietal release under AICRP. Donor parents for Fe and Zn have been identified among exotic germplasms, and the poor agronomic background and photosensitive nature of these donors act as major hindrances. Being naturally enriched with more nutrients than rice and wheat, sorghum and millets value chain is also being strengthened for enhanced consumption of these nutricereals through various efforts by the Indian Institute of Millets Research, Hyderabad (https://millets.res.in; https://www.nutrihubiimr.com/).

**Bioavailability of nutrients becomes critical for successful adoption of the biofortified cereal varieties. Efficacy trials are necessary to convince policy makers about the possibility of integration of biofortified varieties into the food system through the laws of the land, and also farmers and consumers for their adoption. Among biofortified cereals, efficacy trials were demonstrated for vitamin-A orange maize and high Zn maize in African countries. For rice and wheat, only a few efficacy trials were conducted using mostly agronomically or post-harvest biofortified products of rice and wheat as a proof of concept in Bangladesh and Pakistan. The efficacy studies of Zn-biofortified wheat have shown reduction of maternal and child morbidity in India. Four independent studies showed the impact of consumption of biofortified pearl millet on Fe in the target populations of several states in the country.

**Scaling up biofortified cereal varieties**

The introduction of biofortified cereal varieties into the existing cropping systems of India logically should be the replacement of existing popular cereal varieties, for which the biofortified varieties should be nearly similar in yield, quality, duration and agronomic practices. About 70 biofortified cereals have been released in the country for rice, wheat, maize and pearl millet, which are gradually gaining popularity among biofortified cereals, parental lines and some selected germplasm accessions along with a positive correlation between grain Fe and Zn. Based on available variability and stability and the baseline content of Fe as 25–28 mg kg\(^{-1}\) and Zn as 15–18 mg kg\(^{-1}\), the benchmark levels are being proposed for varietal release under AICRP. Donor parents for Fe and Zn have been identified among exotic germplasms, and the poor agronomic background and photosensitive nature of these donors act as major hindrances. Being naturally enriched with more nutrients than rice and wheat, sorghum and millets value chain is also being strengthened for enhanced consumption of these nutricereals through various efforts by the Indian Institute of Millets Research, Hyderabad (https://millets.res.in; https://www.nutrihubiimr.com/).

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supply, licensing and popularization among farmers without any change in the cropping pattern, area or management practices would strengthen the adoption. The integration of these biofortified crops into the food system can be further strengthened through learning from similar experiences of the other countries, where biofortified crops have already been adopted. Distribution of free, small, trial seed packs, informative and attractive flyers and posters, community radio programmes and social media could assist in the popularization of biofortified cereals. Creation of demand and premium price for biofortified grains are the other driving forces for enhanced adoption of biofortified cultivars by the farmers. Studies on willingness to pay for the biofortified cereals showed the importance of extensive and intensive awareness and promotion of biofortified crops.

**Case study of biofortified pearl millet varieties in India**

Collective efforts of HarvestPlus, ICRISAT and ICAR since 2011 resulted in the release of the first-iron rich pearl millet variety in 2014, followed by many other varieties/hybrids. Involvement of private sector has helped in seed production and dissemination of the varieties/hybrids. The biofortified pearl millet varieties have reached the regular seed system as breeder seeds and seed companies as truthfully labelled seeds. The commercial sale of the seeds has been taken up through standardized size packs with attractive primary packaging and mandatory labelling according to the Seeds Act (1996). The demand was created by demonstrations to farmers, field days and promotions at points of sale. The personnel of private seed

### Table 3. Released biofortified maize hybrids with high lysine, tryptophan and provitamin-A

<table>
<thead>
<tr>
<th>Hybrids</th>
<th>Year of release</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pusa Biofortified Maize 1</td>
<td>2020</td>
<td>ICAR-IARI, New Delhi</td>
</tr>
<tr>
<td>Pusa HQPM-5 Improved</td>
<td>2020</td>
<td>ICAR-IARI, New Delhi</td>
</tr>
<tr>
<td>Pusa HQPM-7 Improved</td>
<td>2020</td>
<td>ICAR-IARI, New Delhi</td>
</tr>
<tr>
<td>HQPM-1</td>
<td>2005</td>
<td>ICAR-IMR, Ludhiana</td>
</tr>
<tr>
<td>HQPM-2</td>
<td>2005</td>
<td>ICAR-IMR, Ludhiana</td>
</tr>
<tr>
<td>HQPM-3</td>
<td>2018</td>
<td>ICAR-IMR, Ludhiana</td>
</tr>
<tr>
<td>Malviya Swarna Makka 1</td>
<td>2021</td>
<td>BHU, Varanasi</td>
</tr>
<tr>
<td>Pusa HQPM-1 Improved</td>
<td>2018</td>
<td>ICAR-IARI, New Delhi and CCSHAU, Hisar</td>
</tr>
</tbody>
</table>

### Table 4. Released biofortified pearl millet open-pollinated varieties and hybrids with high iron and zinc

<table>
<thead>
<tr>
<th>Hybrids/varieties</th>
<th>Year of release</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBB 299 (hybrid)</td>
<td>2017</td>
<td>CCSHAU, Hisar</td>
</tr>
<tr>
<td>AHB 1200 Fe (hybrid)</td>
<td>2017</td>
<td>VNMKV, Parbhani</td>
</tr>
<tr>
<td>AHB 1269 Fe (hybrid)</td>
<td>2018</td>
<td>VNMKV, Parbhani</td>
</tr>
<tr>
<td>Phule Mahasakthi (hybrid)</td>
<td>2018</td>
<td>MPKV, Dhule</td>
</tr>
<tr>
<td>RHB 233 (hybrid)</td>
<td>2019</td>
<td>SKNAU, Jobner</td>
</tr>
<tr>
<td>RHB 234 (hybrid)</td>
<td>2019</td>
<td>SKNAU, Jobner</td>
</tr>
<tr>
<td>HBB 311 (hybrid)</td>
<td>2020</td>
<td>CCSHAU, Hisar</td>
</tr>
<tr>
<td>HBB 67 Improved 2 (hybrid) with 15.5% protein</td>
<td>2021</td>
<td>CCSHAU, Hisar</td>
</tr>
</tbody>
</table>

VNMKV, Vasantrao Naik Marathwada Krishi Vidyapeeth; ANGRAU, Acharya NG Ranga Agricultural University; MPKV, Mahatma Phule Krishi Vidyapeeth; SKNAU, Sri Karan Narendra Agricultural University.
companies have been trained in nutrition messaging for
biofortified pearl millet. Around 20,000 ha area was re-
ported to be under cultivation of biofortified pearl millet,
mostly in Maharashtra and Rajasthan.  

Multiple ministries of the Indian Government are im-
plementing several food-grain procurement and distribu-
tion programmes targeting different sections of the needy
population. The integration of biofortified cereals in these
programmes can be a part of practical and cost-effective
strategies to deliver the essential micronutrients like Zn,
Fe and protein to vulnerable communities. Government
policy for procurement and supply of biofortified cereal
grains is essential for their popularization. Initially, bi-
fortified cereals can be procured by states and distributed
to various welfare schemes. This would facilitate the in-
tegration of biofortified cereals in the PDS of the state as a
first step. The procurement can be initially taken up in the
states identified with 184 high-priority districts and 200
high-burden districts for malnutrition (https://niti.gov.in/).
Some states have taken the lead in the introduction of nu-
tricereals like sorghum and millets in the PDS (sorghum and
finger millet in Karnataka), or in social welfare sche-
mes like Anganwadi Services and Integrated Child Devel-
opment Services (ICDS) (under the Ministry of Women
and Child Development, GoI) on a pilot scale (Odisha,
Telangana, Madhya Pradesh), and the mid-day meal
scheme (under the Ministry of Education, GoI) (Karma-
taka, Odisha, Maharashtra, Madhya Pradesh, Andhra Pra-
desh) at the regional level.

Convergence of various schemes like the National Food
Security Mission (NFSM), Rashtriya Krishi Vikas Yojana
(RKVY), ICDS and mid-day meal with the participation of
the Ministries of Agriculture, Women and Child Devel-
opment, Education, Rural Development, Panchayati Raj,
Food Processing Industries, Consumer Affairs, Food and
Public Distribution, Tribal Affairs and Commerce, support-
ed by strong extension and public awareness is essential to
take the benefits of biofortification to the next level. With
the availability of biofortified cereal varieties released
during last five years, the Government has mandated in-
clusion of these nutrient-rich varieties in the frontline
demonstrations organized under NFSM.

**Way forward for biofortified cereals to enhance
human nutrition**

Cereals being the major staple food are ideal targets for
biofortification. According to a recent report, there was
disproportionate increase in the price of non-cereal food,
but that of cereals like rice and wheat was stable during and
after lockdown due to the COVID-19 pandemic. Potential
impact of Zn supplementation on COVID-19 patho-
genesis was suggested to be beneficial for most of the
population, especially those with suboptimal Zn status.
Most of released biofortified cereal varieties of rice, wheat
and pearl millet are high in Zn. Thus, in addition to the
several programmes taken up by the government, integra-
tion of biofortified varieties into the food system could be
one of the significant steps to boost public health. Prelimi-
nary studies at the ICMR-National Institute of Nutrition,
Hyderabad on the bioavailability of Zn in the biofortified
rice variety, DRR Dhan 45 indicated it to be twice that of
the control variety, IR64. Bioavailability of carotenoids is
proportional to the grain carotenoid content, and bioforti-
fied maize (Pro A Hybrid 122 and QPM + Pro-A Hybrid
119) at usual consumption levels can contribute 60–70%
recommended dietary allowances of vitamin-A. Coor-
nilated efforts from policy makers and researchers can
translate the benefits of the biofortified cereals to address
the problem of micronutrient malnutrition in the country.

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inbred for combining high lysine, tryptophan and provitamin A in

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