Review Article

Indian J Med Res 148, November 2018, pp 621-631
DOI: 10.4103/ijmr.IJMR_1893_18

Quick Response Code:

Nutritional security through crop biofortification in India: Status & future prospects

Devendra Kumar Yadava, Firoz Hossain & Trilochan Mohapatra

Indian Council of Agricultural Research, Ministry of Agriculture & Farmers Welfare, Government of India, New Delhi, India

Received October 12, 2018

Malnutrition has emerged as one of the most serious health issues worldwide. The consumption of unbalanced diet poor in nutritional quality causes malnutrition which is more prevalent in the underdeveloped and developing countries. Deficiency of proteins, essential amino acids, vitamins and minerals leads to poor health and increased susceptibility to various diseases, which in turn lead to significant loss in Gross Domestic Product and affect the socio-economic structure of the country. Although various avenues such as dietary-diversification, food-fortification and medical-supplementation are available, biofortification of crop varieties is considered as the most sustainable and cost-effective approach where the nutrients reach the target people in natural form. Here, we have discussed the present status on the development of biofortified crop varieties for various nutritional and antinutritional factors. Ongoing programmes of the Indian Council of Agricultural Research on the improvement of nutritional traits in different crops have been presented. Challenges and future prospects of crop biofortification in India have also been discussed. The newly developed biofortified crop varieties besides serving as an important source for livelihood to poor people assume great significance in nutritional security.

Key words Biofortification - crop varieties - hidden hunger - malnutrition - nutritional security

Malnutrition: A widespread phenomenon

Malnutrition poses serious socio-economic implications worldwide, more specifically in the underdeveloped and developing countries[1]. Caused due to inadequate consumption of balanced diet, malnutrition leads to poor health, increased susceptibility to various diseases and significant loss of annual Gross Domestic Product (GDP), which is as high as 11 per cent in Asia and Africa[2]. Globally, around two billion people suffer from malnutrition, while 815 million people are undernourished. Children are the most affected due to malnutrition, as a result 151 million children under the age of five are stunted, while 51 million do not weigh enough according to height (wasting)[3]. Nearly 45 per cent of deaths among children under the age of five are associated with malnutrition. The problem is so widespread that 88 per cent of the countries experience two or three forms of malnutrition. Among various parts of the globe, Southern Asia is affected the most by malnutrition with 33.3 and 15.3 per cent of the children (<5 yr) are stunted and wasted compared to global average of 22.2 and 7.5 per cent, respectively[3]. In India, 21.9 per cent of the population lives in extreme poverty, and it is estimated that 15.2 per cent of people are undernourished[4]. As per the National Family Health Survey-4 (2015-2016)[5], 38.4 per cent of the Indian children (<5 yr) are stunted, 21.0 per cent are wasted and 35.7 per cent of the children are underweight. Anaemia is also a serious health issue, where 58.4 per cent of the Indian children (6-59 months) and 53 per cent of the adult women (15-49 yr) are affected from this deficiency. The figure is also alarming among adult males as 22.7 per cent were found to be anaemic.

Considering its widespread ramification, alleviation of malnutrition has been identified as one of the most important steps for hunger-free world. At the beginning of the new millennium, world leaders set eight 'Millennium Development Goals' (MDGs), of which (*i*) eradication of extreme poverty and hunger (Goal 1), (*ii*) reduction of child mortality (Goal 4), and (*iii*) improvement of maternal health (Goal 5), pertain to providing healthy and nutritious food to the people worldwide[6]. During 2015, the global community further set 'Sustainable Development Goals (SDGs)' which aim to end malnutrition in all its form[2]. Of the 17 goals, SDG2 (Zero Hunger) aims to end hunger through improved food and nutritional security. SDG3 (Good Health and Well-being) aims to ensure healthy lives and promotes well-being of people at all ages. Twelve of the 17 goals are highly linked to nutrition thereby signifying its role for better health, education, employment and female empowerment. It has now been estimated that alleviating malnutrition is one of the most cost-effective steps as it offers the benefit of $16 with every $1 invested in any proven nutrition programme[2].

Tackling malnutrition

Unbalanced proportion of micronutrients in the diet causes various health problems, and popularly phrased as 'hidden hunger'. Three major strategies are generally followed to address malnutrition[7]. The most desirable approach is to increase the diversity of food intake - a process referred to as 'dietary-diversification'. Cereal-based diet is the mainstay of food among the resource poor. The inclusion of pulse, fruits and vegetables and even animal proteins in the diet makes the food more balanced. However, practising 'dietary-diversification' may not be feasible in many developing countries, especially among low-income populations. Further, it is often limited by crop seasonality and low bioavailability of specific micronutrients[8]. The second approach deals with the addition of nutrients artificially, either by providing supplements such as vitamin A and iron pills/capsules (medical supplementation) or by adding nutrients in basic food products such as iodized salt (food fortification). Iron- and folate-fortified flour, and vitamin A added cooking oil are also some of the popular examples of fortification. However, these approaches are not sustainable over the longer term because it relies on a robust distribution, infrastructure and consumer compliance[9]. Poor infrastructure in developing countries further limits the widespread use of supplementation. The effective coordination between different agencies is also an important factor for successful implementation. Lack of purchasing power of the poor due to poverty restricts the access to the fortified foods, thereby reducing their efficiency and application. While each of the three approaches is effective under ideal situations, 'biofortification' remains the most sustainable and cost-effective mean for providing the desired levels of nutrients in the diet in natural form[10]. Biofortification is a process where the nutritional quality of a crop is enhanced through genetic manipulation that includes both breeding and transgenic approaches[11]. Among various nutrients, protein, lysine, tryptophan, iron, zinc, vitamin A and vitamin C are essential for human nutrition, and their deficiency leads to various symptoms and health disorders. Erucic acid, glucosinolates and Kunitz trypsin inhibitor (KTI) are the antinutritional factors as their consumption in higher levels leads to adverse effects in humans and livestock. Function and deficiency symptoms of the important nutrients are presented below.

Nutritional factors

Protein: It provides essential amino acids for growth and tissue repair. Humans require 0.66 g protein/kg body weight/day to meet the requirement for proper growth and development[12]. Deficiency in protein leads to poor intellectual development, disorderly physical functioning and even mortality. Diet deficient in protein leads to kwashiorkor and marasmus among humans.

Lysine: It is a building block in protein synthesis besides serving as precursor for several neurotransmitters and metabolic regulators. The daily lysine requirement is 30 mg/kg body weight/day for adults, while it is 35 mg/kg body weight/day for children of 3-10 yr of age[12]. Deficiency leads to fatigue, dizziness, nausea, anaemia, delayed growth, loss of appetite and reproductive tissue[13,14].

Tryptophan: It is also a building block of proteins, and functions as precursors for several neurotransmitters and regulators of metabolic pathways. Tryptophan is required at the rate of 4 mg/kg body weight/day in adults and 4.8 mg/kg body weight/day in children (3-10 yr)[12]. Its deficiency leads to depression, anxiety and impatience. Weight loss and slow growth in children are the major symptoms of tryptophan deficiency[13,14].

Iron: It is a mineral element which humans require for the proper functioning of muscle and brain tissues. It serves as the transport medium for electrons within cells and also carries oxygen from the lungs to various tissues by red blood cell haemoglobin. It is an integral part of important enzyme systems in various tissues. Estimated average requirement (EAR) of iron for non-pregnant and non-lactating women is 1460 µg/g, while it is 500 µg/g per day for children of 4-6 yr[15]. The occurrence of anaemia is the most common characteristics of iron deficiency in human. It affects overall growth and development, besides causing mild mental retardation and goitre thereby severely affecting the work productivity[16].

Zinc: It is a mineral element which serves as cofactor in as many as 300 enzymes required for human metabolism. It is required for the regulation of synthesis and degradation of nucleic acids, proteins, lipids and carbohydrates. Zinc also plays vital role in maintaining cellular integrity and immune system. The EAR of zinc for non-pregnant and non-lactating women is 2960 µg/g, while it is 1390 µg/g per day in case of children of 4-6 yr[15]. The clinical symptoms of severe zinc deficiency are retardation in growth associated with delayed sexual and bone maturation. Loss of appetite, impaired immune function, increased susceptibility to infections such as diarrhoea besides skin lesion also occurs as a result of zinc deficiency[17].

Vitamin A: Also called as retinol, vitamin A is essentially required for the normal functioning of the visual system, growth and development, maintenance of epithelial cell integrity, immune system and reproduction. The requirement of vitamin A in non-pregnant and non-lactating women is 500 µg/g, while it is 275 µg/g per day in case of children of 4-6 yr[15]. Night blindness is the hallmark of an early symptom of vitamin A deficiency. Xerophthalmia and keratomalacia caused due to structural alterations of the conjunctiva and cornea may also follow. In severe deficiency, it may lead to irreversible blindness. Further, chances of anaemia, diarrhoea, measles, malaria and respiratory infections are also enhanced[18].

Vitamin C: It is also called ascorbic acid and required for metabolism and repair of various tissues such as skin, bone, teeth and cartilage. Vitamin C is also used to increase iron absorption from the gastrointestinal tract. The recommended dietary allowance for vitamin C in adult women is 60 mg per day, while it is 90 mg/day in adult men[19]. Deficiency leads to scurvy which is characterized by bleeding gums, bruising and poor wound healing in the teeth and is also associated with joint and muscle pains.

Anti-nutritional factors

Erucic acid: It is a monounsaturated fatty acid found especially in mustard and rapeseed oil. High concentration of erucic acid in edible oils impairs myocardial conductance, causes lipidosis in children and increases blood cholesterol, <2.0 per cent of erucic acid in oil is desirable for health[20,21].

Glucosinolates: It is a group of thioglucosides mainly found in *Brassicaceae* family. Glucosinolates produce glucose, sulphate and other aglucon products when broken down by myrosinase. Higher consumption is detrimental to animal health as these reduce the feed palatability and affect the iodine uptake by the thyroid glands, which in turn lowers feed efficiency and weight gains particularly in non-ruminants such as pigs and poultry; <30 ppm of glucosinolates in seed meal is desirable[21,22].

Kunitz trypsin inhibitor (KTI): It is a non-glycosylated protein that possesses adverse effects on growth of humans primarily through inhibition of trypsin in the digestive tract leading to indigestion. KTI constituting the major portion of total trypsin inhibitors in soybean, is considered detrimental to human health[23]. Although heat treatment is used to get rid of this heat labile protein, the entire amount is not removed.

Biofortified crop cultivars: The National Agricultural Research System (NARS) including Indian Council of Agricultural Research (ICAR) institutes and State Agricultural Universities (SAUs) have contributed immensely to make India self-sufficient in food production. From 50.82 mt of food production in 1950-1951, India has touched 284.8 mt during

2017-2018 (Fourth Advance Estimates)[24]. Similarly, horticulture crops have also experienced increase from 96.56 mt during 1991-1992 to 306.8 mt during 2017-2018 (Third Advance Estimates)[24]. The tremendous gain achieved in yield potential has been possible due to the development and deployment of high yielding varieties and heterotic hybrids - the efforts initiated during Green Revolution. So far NARS has developed 4723 varieties of various field crops. However, in the process of yield enhancement, nutritional quality was not given due importance, and as a result, majority of these varieties do not possess the desired level of nutritional quality. Realizing the paramount importance of nutritional quality, research efforts of NARS have now led to the development and release of a series of biofortified varieties through All Indian Coordinated Research Projects (AICRPs) for different crops[25]. The biofortified varieties not only provide enough calories but also deliver essential nutrient(s) needed for adequate growth and development. The baseline (available in the traditional cultivar) and higher levels achieved in some of the important nutrients in selected crops of the country are presented in the Table. The details of the some of the recently developed biofortified cultivars released through AICRP network are presented below:

Rice

CR Dhan 310: It is a pure line variety and contains high protein (10.3%) in polished grain. It has been released and notified in 2016 for Odisha, Madhya Pradesh and Uttar Pradesh. Its average grain yield is 45.0 q/ha (quintal/hectare). It matures in 125 days[21,25]. This biofortified variety has been developed by ICAR-National Rice Research Institute, Cuttack, Odisha.

Table. Details of baseline level of nutrients in targeted crops and levels achieved through biofortification

Crop	Nutrient	Baseline levels	Levels achieved
Nutritional factor			
Rice[21,25]	Zinc	12.0-16.0 ppm	>20.0 ppm
	Protein	7.0-8.0%	>10.0%
Wheat[21,25]	Iron	28.0-32.0 ppm	>38.0 ppm
	Zinc	30.0-32.0 ppm	>40.0 ppm
	Protein	8-10%	>12.0%
Maize[21,25-27]	Lysine	1.5-2.0%	>2.5%
	Tryptophan	0.3-0.4%	>0.6%
	Provitamin A	1-2 ppm	>8.0 ppm
Pearl millet[21,25]	Zinc	30.0-35.0 ppm	>40.0 ppm
	Iron	45.0-50.0 ppm	>70.0 ppm
Lentil[21,25]	Zinc	35-40 ppm	>50.0 ppm
	Iron	45-50 ppm	>62.0 ppm
Cauliflower[21,25]	β-carotene	Negligible	>8.0 ppm
Sweet potato[21,25]	Anthocyanin	Negligible	>80.0 mg/100 g
	β-carotene	2.0-3.0 mg/100 g	>13.0 mg/100 g
Pomegranate[21,25]	Vitamin C	14.2-14.6 mg/100 g	>19.0 mg/100 g
	Iron	2.7-3.2 mg/100 g	>5.0 mg/100 g
	Zinc	0.50-0.54 mg/100 g	>0.6 mg/100 g
Anti-nutritional factor			
Mustard[20,21,25]	Glucosinolates	>120.0 ppm	<30.0 ppm
	Erucic acid	>40%	<2.0%
Soybean[21,23]	Kunitz trypsin inhibitor	30-45 mg/g of seed meal	Negligible

DRR Dhan 45: It is a pure line variety and possesses high zinc (22.6 ppm) in polished grain. It has been released and notified in 2016 for Karnataka, Tamil Nadu, Andhra Pradesh and Telangana. Its average grain yield is 50.0 q/ha. It matures in 125-130 days[21,25]. This biofortified variety has been developed by ICAR-Indian Institute of Rice Research, Hyderabad, Telangana.

DRR Dhan 49: It is a pure line variety with high zinc (25.2 ppm) in polished grain. It has been released and notified in 2018 for Gujarat, Maharashtra and Kerala. Its average grain yield is 50.0 q/ha. It matures in 125-130 days[21]. This biofortified variety has been developed by ICAR-Indian Institute of Rice Research, Hyderabad, Telangana.

Wheat

WB 02: It is a pure line variety and rich in zinc (42.0 ppm) and iron (40.0 ppm). It has been released and notified in 2017 for Punjab, Haryana, Delhi, Rajasthan (excluding Kota and Udaipur division), western Uttar Pradesh (except Jhansi division), Jammu and Kathua district of Jammu and Kashmir, Paonta Valley and Una district of Himachal Pradesh and Tarai region of Uttarakhand. Its average grain yield is 51.6 q/ha. It matures in 142 days and is suitable for irrigated timely sown conditions[21,25]. This biofortified variety has been developed by ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana.

HPBW 01: It is a pure line variety and contains high iron (40.0 ppm) and zinc (40.6 ppm). It has been released and notified in 2017 for Punjab, Haryana, Delhi, Rajasthan (excluding Kota and Udaipur division), western Uttar Pradesh (except Jhansi division), Jammu and Kathua district of Jammu and Kashmir, Paonta Valley and Una district of Himachal Pradesh and Tarai region of Uttarakhand. Its average grain yield is 51.7 q/ha. It matures in 141 days and is suitable for irrigated timely sown conditions[21,25]. This biofortified variety has been developed by Punjab Agricultural University, Ludhiana, Punjab, under ICAR-All India Coordinated Research Project on Wheat and Barley.

Pusa Tejas (HI 8759): It is a pure line variety with high protein (12%), iron (42.1 ppm) and zinc (42.8 ppm). It is a durum wheat variety suitable for making *chapatti* (Indian bread), pasta and other traditional food products. It has been released and notified in 2017 for Madhya Pradesh, Chhattisgarh, Gujarat, Rajasthan and Uttar Pradesh. The average yield of this variety is 50.0 q/ha under timely sown irrigated conditions[21]. This biofortified variety has been developed by ICAR-Indian Agricultural Research Institute (IARI), Regional Station, Indore, Madhya Pradesh.

Pusa Ujala (HI 1605): It is a pure line variety with high protein (13%), iron (43 ppm) and zinc (35 ppm) and having excellent *chapatti* making quality. It has been released and notified in 2017 for Maharashtra, Karnataka and Tamil Nadu. Its average yield is 30.0 q/ha under timely sown, restricted irrigation conditions[21]. This biofortified variety has been developed by ICAR-IARI, Regional Station, Indore, Madhya Pradesh.

MACS 4028 (d): It is a pure line durum wheat variety with high protein (14.7%), iron (46.1 ppm) and zinc (40.3 ppm). It has been released and notified in 2018 for Maharashtra and Karnataka. Its average grain yield is 19.3 q/ha under rainfed low fertility, timely sown conditions in Peninsular Zone. It matures in 102 days[21]. This biofortified variety has been developed by Agharkar Research Institute, Pune, Maharashtra, under ICAR-All India Coordinated Research Project on Wheat and Barley.

Maize

Pusa Vivek QPM9 improved: It is an early maturing hybrid and possesses high provitamin-A (8.15 ppm). It also contains high tryptophan (0.74%) and lysine (2.67%) in endosperm protein and known as 'quality protein maize' (QPM). It is also a multi-nutrient maize hybrid. It has been released and notified in 2017 for Jammu and Kashmir, Himachal Pradesh, Uttarakhand (Hills), North Eastern States, Maharashtra, Karnataka, Andhra Pradesh, Telangana and Tamil Nadu. Its average grain yield is 55.9 and 59.2 q/ha, with maturity of 93 and 83 days in the two different agro-climatic zones, respectively[21,25]. This biofortified variety has been developed by ICAR-IARI, New Delhi.

Pusa HM4 improved: It is a medium maturing QPM hybrid that possesses high tryptophan (0.91%) and lysine (3.62%) in endosperm protein. It has been released and notified in 2017 for Punjab, Haryana, Delhi, Uttarakhand (plains) and western Uttar Pradesh. Its average grain yield is 64.2 q/ha. It matures in 87 days[21,25]. This biofortified variety has been developed by ICAR-IARI, New Delhi.

Pusa HM8 improved: It is a medium maturing QPM hybrid that possesses high tryptophan (1.06%) and lysine (4.18%) in endosperm protein. It has been released and notified in 2017 for Maharashtra, Karnataka, Andhra Pradesh, Telangana and Tamil Nadu. Its average grain yield is 62.6 q/ha. It matures in 95 days[21,25]. This biofortified variety has been developed by ICAR-IARI, New Delhi.

Pusa HM9 improved: It is a medium maturing QPM hybrid that possesses high tryptophan (0.68%) and lysine (2.97%) in endosperm protein. It has been released and notified in 2017 for Bihar, Jharkhand, Odisha, West Bengal and eastern Uttar Pradesh. Its average grain yield is 52.0 q/ha. It matures in 89 days[21,25]. This biofortified variety has been developed by ICAR-IARI, New Delhi.

Besides, Shakti-1 (composite) and hybrids, namely Shaktiman-1, Shaktiman-2, HQPM-1, Shaktiman-3, Shaktiman-4, HQPM-5, HQPM-7, Vivek QPM-9, HQPM-4, Pratap QPM Hybrid-1 and Shaktiman-5, have also been released for various agroecologies of the country under the AICRP system. These cultivars possess high protein quality due to a higher concentration of lysine and tryptophan.

Pearl millet

HHB 299: It is a hybrid and possesses high iron (73.0 ppm) and zinc (41.0 ppm) content. It has been released and notified in 2017 for Haryana, Rajasthan, Gujarat, Punjab, Delhi, Maharashtra and Tamil Nadu. Its average grain yield is 32.7 q/ha, and dry fodder yield is 73.0 q/ha. It matures in 81 days[21,25]. This biofortified variety has been developed by Chaudhary Charan Singh-Haryana Agricultural University, Hisar in collaboration with International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Hyderabad, Telangana, under ICAR-All India Coordinated Research Project on Pearl millet.

AHB 1200: It is a hybrid and rich in iron (73.0 ppm). It has been released and notified in 2017 for Haryana, Rajasthan, Gujarat, Punjab, Delhi, Maharashtra and Tamil Nadu. Its average grain yield is 32.0 q/ha; dry fodder yield is 70.0 q/ha. It matures in 78 days[21,25]. This biofortified variety has been developed by Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, in collaboration with ICRISAT, Patancheru, Hyderabad, Telangana, under ICAR-All India Coordinated Research Project on Pearl millet.

Lentil

Pusa Ageti Masoor: It is a pure line variety and contains 65.0 ppm iron. It has been released and notified in 2017 for Uttar Pradesh, Madhya Pradesh and Chhattisgarh. Its average grain yield is 13.0 q/ha. It matures in 100 days and is suitable for the rainfed condition[21,25]. This biofortified variety has been developed by ICAR-IARI, New Delhi.

IPL 220: It is a pure line variety with high iron (73 ppm) and zinc (51 ppm). It has been released and notified during 2018 for eastern Uttar Pradesh, Bihar, Assam and West Bengal. The average yield of IPL-220 is 13.8 q/ha. It matures in 121 days and is suitable for the rainfed situation during rabi season[21]. This biofortified variety has been developed by ICAR-Indian Institute of Pulses Research, Kanpur, Uttar Pradesh.

Mustard

Pusa Mustard 30: It is a pure line variety and contains low erucic acid (<2.0%) in oil. It has been released and notified in 2013 for Uttar Pradesh, Uttarakhand, Madhya Pradesh and Rajasthan. Its average oil content is 37.7 per cent, with a seed yield of 18.2 q/ha. It matures in 137 days and is suitable for timely sown irrigated conditions[21,25]. This biofortified variety has been developed by ICAR-IARI, New Delhi.

Pusa Double Zero Mustard 31: It is a pure line variety and contains low erucic acid (<2.0%) in oil and glucosinolates (<30.0 ppm) in seed meal. It has been released and notified in 2016 for Rajasthan (north and western parts), Punjab, Haryana, Delhi, western Uttar Pradesh, plains of Jammu and Kashmir and Himachal Pradesh. Its average oil content is 41.0 per cent, with a seed yield of 23.0 q/ha. It matures in 142 days and is suitable for timely sown irrigated conditions[21,25]. This biofortified variety has been developed by ICAR-IARI, New Delhi.

Soybean

NRC-127: It is a KTI-free pure line soybean variety. It has been released in 2018 for Madhya Pradesh, Bundelkhand region of Uttar Pradesh, Rajasthan, Gujarat and Marathwada and Vidarbha region of Maharashtra. The average yield of NRC-127 is 18.0 q/ha, and it matures in 104 days. It has 18.5-20.0 per cent oil and 38.0-40.0 per cent protein content[21]. This biofortified variety has been developed by ICAR-Indian Institute of Soybean Research, Indore, Madhya Pradesh.

Cauliflower

Pusa Beta Kesari 1: It is a pure line variety and contains high β-carotene (8.0-10.0 ppm). It has been released and notified in 2015 for the Nation Capital Region of Delhi. Its average curd yield is 40.0-50.0 t/ha[21,25]. This biofortified variety has been developed by ICAR-IARI, New Delhi.

Sweet potato

Bhu Sona: It is a pure line variety and contains high β-carotene (14.0 mg/100 g). It has been released and notified in 2017 for Odisha. Its average tuber yield is 19.8 t/ha with dry matter of 27.0-29.0 per cent, starch of 20.0 per cent and total sugar of 2.0-2.4 per cent[21,25]. This biofortified variety has been developed by ICAR-Central Tuber Crops Research Institute (CTCRI), Thiruvananthapuram, Kerala.

Bhu Krishna: It is a pure line variety and contains high anthocyanin (90.0 mg/100 g). It has been released and notified in 2017 for Odisha. Its average tuber yield is 18.0 t/ha, with dry matter of 24.0-25.5 per cent, starch of 19.5 per cent and total sugar of 1.9-2.2 per cent[21,25]. This biofortified variety has been developed by ICAR-CTCRI, Thiruvananthapuram, Kerala.

Pomegranate

Solapur Lal: It is a hybrid variety and contains high iron (5.6-6.1 mg/100 g), zinc (0.64-0.69 mg/100 g) and vitamin C (19.4-19.8 mg/100 g) in fresh arils. It has been released and notified in 2017 for semi-arid regions of the country. Its average fruit yield is 23.0-27.0 t/ha[21,25]. This biofortified variety has been developed by ICAR-National Research Centre on Pomegranate, Pune, Maharashtra.

Global impact of biofortified varieties

The deployment of biofortified cultivars holds great promise for health and wellbeing of the human population. Several studies have demonstrated the positive effects of these biofortified crops on humans. A study conducted on 246 children of 12-16 yr of age in Maharashtra, by feeding them with '*bhakri*' (round flat unleavened bread) made from iron-rich and conventional pearl millet grains, demonstrated that feeding iron-rich pearl millet was an efficient approach to improve iron status in school-age children[28]. In another, serum xanthophylls and retinol were significantly improved in Zambia children fed with provitamin-A rich maize grains[29]. In a study on 679 Zambian children, it was found that consumption of β-carotene-rich maize significantly improved their serum β-carotene concentrations compared with traditional maize[30]. The beneficial effects of QPM are also well-demonstrated worldwide. Porridge made from QPM resulted in fewer sick days among children compared to those who had porridge from normal maize. Infants and young children fed with QPM expressed 12 per cent higher rate of growth in weight and nine per cent in height compared to the group given only normal maize[31]. Another study showed that consumption of 100 g QPM was sufficient for children to meet the requirement of lysine resulting into reduction in maize to the tune of 40 per cent relative to normal maize[32]. The orange-fleshed sweet potatoes (OFSP) were fed to South African school children aged 5-10 yr, and a favourable response in the vitamin-A status of children was observed compared with the children fed with a traditional white variety of sweet potato[33]. In Mozambique, children who consumed OFSP over the two-year intervention possessed significantly higher serum retinol concentrations compared with non-intervened children[34]. The development and promotion of biofortified varieties thus would be helpful in addressing malnutrition and achieving the SDGs[35].

Future prospects

Intensive efforts by public sector institutions and policy for intense promotional campaigns can effectively ensure a significant increase in the adoption and acceptance of biofortified crop varieties. Strengthening the seed chain to produce and supply good quality seeds is one of the important steps for the popularizing biofortified varieties. The maintenance of genetic purity is very essential for keeping the quality trait intact; hence, special seed production areas need to be identified. Seed village programme can also be one option for taking the seed/commercial production of such varieties to avoid outcrossing from other conventional varieties. Providing subsidized seeds and other inputs would further contribute to the rapid dissemination of nutritionally improved cultivars among the farmers. Assured premium remunerative price through minimum support price for biofortified grains in the market will encourage the farmers to grow more biofortified crops. Investment on extension activities would make the farmers, industry and consumers aware of the availability and benefits of biofortified crops. Essential interventions required for research, development and popularization of biofortified crop varieties have been discussed below:

Awareness generation

Lack of awareness on the health benefits of biofortified crops is one of the major factors for slow adoption of biofortified varieties. Educational background of the household head and the extent of farmers' participation in demonstration trials and field days are the important factors for the generation of awareness[36,37]. Further, the decision by households to adopt biofortified crops and the subsequent decision to allocate the nutritious food to young children are also the significant factors for having impacts on children's nutrition and health[38]. The apprehension of low yielding potential of biofortified varieties has also been identified as the other important factor for slow popularization among the farmers. It is now well established that the biofortified varieties are comparable to traditional varieties for their yield potential[26,27]. In cases, where enrichment of nutrients such as provitamin-A and anthocyanin leads to the altered appearance of the produce (yellow vs. white maize, and white vs. yellow/purple sweet potato), consumers at the village level generally hesitate in accepting the biofortified produce as food[39]. Some of the nutritional traits (lysine and tryptophan) are governed by recessive genes and contamination by foreign pollen from neighbouring fields dilutes the quality of the produce in the cross-pollinated crops. This warrants adoption of 'seed village' model for the cultivation of the biofortified crops by the entire farming community of the village. In case of maize, weak linkages between farmers and local poultry firms have also been identified as a significant factor for lesser usage of biofortified grains as animal feed[40]. Further, strong linkages with agrifood-processing industry would help in the dissemination of biofortified crops. Strong promotional extension activity such as field demonstration, conveying a message through TV talk, radio shows and live-drama would make the farmers, industry and consumers aware of the existence and benefits of biofortified crops.

Policy support

Strengthening the seed chain to produce and supply good quality seeds is an important step for the popularization of biofortified varieties of different crops. Providing subsidized seeds and other inputs would further contribute to the rapid dissemination of nutritionally improved cultivars among the farmers. Assurance of remunerative price through minimum support price and/or premium price for biofortified grains in the market will also encourage the farmers to grow more biofortified crops. Recently, unveiled National Nutrition Strategy - 2017 by NITI Aayog, Government of India envisages alleviation of malnutrition in the country through food-based solution[21]. Inclusion of these biofortified cereals in different government sponsored programmes such as National Food Security Mission, *Rashtriya Krishi Vikas Yojna* as well as nutrition intervention programme such as Integrated Child Development Services scheme, 'Mid-day meal' and Nutrition Education and Training through Community Food and Nutrition Extension Units would help in providing the much needed balanced food to poor people. The central government has recently declared millets (sorghum, pearl millet, foxtail millet, finger millet, kodo millet, proso millet, little millet and barnyard millet) besides two pseudo millets (buck-wheat and amaranthus) which have high nutritive value as 'Nutri Cereals'[21]. This would boost their demand and allow farmers to get higher prices. The inclusion of biofortified products in these government-sponsored schemes would especially benefit the children, pregnant women and elderly people, and would help in their quick dissemination. Considering the well-demonstrated health benefits of QPM, the Government of Ethiopia has set a target to have QPM varieties cultivated on 20 per cent of the country's total maize area in the coming few years[38]. Thus, strong policy support from the government would further increase the adoption and acceptance of biofortified crops.

Research interventions

Most of the nutritional traits are phenotypically invisible (protein, lysine, tryptophan, iron, zinc and vitamin C), hence difficult to convince the farmers and traders regarding the extent of quality of the produce[41]. Brix meter is one such example where sugar content is measured in the harvest of sugarcane and sweet corn. The development of hand-held and easy to use equipment that can quickly provide some reliable estimates of the quality parameters of the produce would be beneficial. Besides, research should be initiated to breed for new traits that are not part of currently available biofortified cultivars. In this direction, to further expedite the process of development of biofortified crops, ICAR has recently funded a Consortia Research Platform on 'Biofortification in Selected Crops for Nutritional Security', where rice, wheat, maize, pearl millet, sorghum and minor millets have been targeted for nutritional enrichment[42]. Phytic acid has been identified as one of the most important anti-nutritional factors that reduces the bioavailability of iron and zinc in our body. In human gut, only 7-7.5 per cent of iron and 15-25 per cent of zinc in food grains are available for absorption[15]. Genetic variation on the activity of phytase enzyme that degrades phytic acid has been found in wheat, and specific germplasm lines with high phytase activity is being used as donors in the breeding programme.

In rice and maize, low-phytic acid mutants (*lpa*) that lead to lower synthesis of phytic acid are being used in the breeding progarmme[42]. Similarly, high oil trait that enhances bioavailability of provitamin A in maize has been targeted for introgression. There is also a need to breed for promoting factors such as ascorbic acid and β-carotene that enhance the bioavailability of iron and zinc[11]. Besides, development of multi-nutrient rich cultivars is also a viable option to simultaneously address deficiency of several nutrients. Three multinutrient rich cultivars namely (*i*) 'Pusa Tejas'- wheat variety rich in protein, iron and zinc, (*ii*) 'Pusa Vivek QPM9 Improved' - maize hybrid rich in provitamin A, lysine and tryptophan, and (*iii*) 'Solapur Lal' - a pomegranate variety with high vitamin C, iron and zinc, have been developed. Maize genotypes with four nutritional traits namely high lysine, tryptophan, provitamin A and vitamin E have been developed and currently under evaluation at multilocations. The utilization of modern tools and techniques should be the integral part of all breeding programmes. Genomics-assisted breeding coupled with doubled haploid and speed-breeding technologies would further accelerate the development of biofortified cultivars. Wherever sufficient genetic variation for the target trait is not present in the available germplasm, transgenic approach assumes significance. In this direction, NARS has made efforts and 'golden rice' lines with high provitamin A have been developed. Better coordination and collaboration among various subject specialists namely breeders, biotechnologists, biochemists, seed technologists, agronomists and post-harvest technologists across various public and private organizations would further drive the development of nutritionally rich crop varieties in a more effective way.

Efficacy trials on the effects of our biofortified varieties on the Indian population need to be undertaken on a priority. Under the ICAR-CRP on Biofortification, ICAR-IARI, New Delhi in collaboration of ICMR-National Institute of Nutrition, Hyderabad have analyzed the bioaccessibility of provitamin A maize using *in vitro* model system, and the results are quite encouraging[43]. Taking leads from this study, a human clinical trial has now been planned to evaluate the effects of provitamin A rich maize on humans. Provitamin A rich maize fed chickens is also an effective way for improving vitamin A consumption among non-vegetarians populations through eggs[44]. The ICAR-IARI, New Delhi, in collaboration of ICAR-Directorate of Poultry Research, Hyderabad has initiated a programme to evaluate the effects of provitamin A rich maize on indigenous poultry breed, *Vanaraja*. Large-scale trials would further help in generating data and thus help in dissemination of biofortified varieties. Since nutritional traits such as minerals and vitamins do not affect the grain yield, these need to be brought into the mainstream where varieties across crops developed in future should possess at least set level of one/few selected nutritional traits. The high yielding biofortified crops assume great significance for nutritional security. The father of Green Revolution, Prof. M.S. Swaminathan has rightly said that 'we need to move from food security to nutrition security, where not only calories and proteins but also micronutrients are taken care of. All that needs to be done is to bring agriculture, health and nutrition together in a triangular relationship, which can only be achieved through partnerships'[45].

***Acknowledgment*:** Contributions of all the scientists associated in developing these varieties and sponsoring Institutes/SAUs in providing the information are acknowledged.

***Financial support & sponsorship*:** None.

***Conflicts of Interest*:** None.

References

1. Bouis H. Reducing mineral and vitamin deficiencies through biofortification: Progress under HarvestPlus. In: Biesalski HK, Birner R, editors. *Hidden hunger: Strategies to improve nutrition quality, World review of nutrition and dietetics*. Basel: Karger; 2018. p. 112-22.
2. Global Nutrition Report. *Nourishing the SDGs*. Bristol, UK: Development Initiatives; 2017.
3. UNICEF/WHO/WB Group. *Joint child malnutrition estimates - Levels and trends in child malnutrition.* New York, Geneva, Washington, DC: UNICEF, WHO, The World Bank; 2018.
4. International Food Policy Research Institute. *Global food policy report*. Washington, DC: IFPRI; 2016.
5. International Institution for Population Sciences. *National family health survey* - 4, 2015-16. Mumbai: IIPS; 2017.
6. United Nations General Assembly. *United Nations millennium declaration. A/RES/55/2*. UN General Assembly; 2000. Available form: *https://www.unescap.org/resources/ga-resolution-552-united-nations-millennium-declaration*, accessed on October 12, 2018.
7. Gómez-Galera S, Rojas E, Sudhakar D, Zhu C, Pelacho AM, Capell T, *et al.* Critical evaluation of strategies for mineral

fortification of staple food crops. *Transgenic Res* 2010; *19* : 165-80.

8. van Lieshout M, de Pee S. Vitamin A equivalency estimates: Understanding apparent differences. *Am J Clin Nutr* 2005; *81* : 943-5.

9. International Zinc Nutrition Consultative Group (IZiNCG), Brown KH, Rivera JA, Bhutta Z, Gibson RS, King JC, *et al*. International Zinc Nutrition Consultative Group (IZiNCG) technical document #1. Assessment of the risk of zinc deficiency in populations and options for its control. *Food Nutr Bull* 2004; *25*(1 Suppl 2) : S99-203.

10. Pfeiffer WH, McClafferty B. HarvestPlus: Breeding crops for better nutrition. *Crop Sci* 2007; *47* : S88-105.

11. Welch RM, Graham RD. Breeding for micronutrients in staple food crops from a human nutrition perspective. *J Exp Bot* 2004; *55* : 353-64.

12. Joint WHO/FAO/UNU Expert Consultation. Protein and amino acid requirements in human nutrition. WHO technical report series No- 935. Geneva; WHO; 2007.

13. Tome D, Bos C. Lysine requirement through the human life cycle. *J Nutr* 2007; *137* : 1642S-1645S.

14. Moehn S, Pencharz PB. Ball RO. Lessons learned regarding symptoms of tryptophan deficiency and excess from animal requirement studies. *J Nutr* 2012; *142* : 2231S-2235S.

15. Andersson MS, Saltzman A, Virk PS, Pfeiffer WH. Progress update: Crop development of biofortified staple food crops under Harvestplus. *Afr J Food Agric Nutr Dev* 2017; *17* : 11905-35.

16. Scrimshaw NS. Functional consequences of iron deficiency in human populations. *J Nutr Sci Vitaminol*, 1984; *30* : 47-63.

17. Prasad AS. Zinc deficiency in women, infants and children. *J Am Coll Nutr* 1996; *15* : 113-20.

18. West CE. Vitamin A and measles. *Nutr Rev* 2000; *58* : S46-54.

19. Food and Agricultural Organization/World Health Organization. *Preliminary report on recommended nutrient intakes. Joint FAO/WHO expert consultation on human vitamin and mineral requirements*. Rome, Italy, Geneva, Switzerland, Bangkok, Thailand: FAO/WHO and World Health Organization; 13 July, 2000.

20. Saini N, Singh N, Kumar A, Vihan N, Yadav S, Vasudev S, *et al.* Development and validation of functional CAPS markers for the FAE genes in *Brassica juncea* and their use in marker-assisted selection. *Breed Sci* 2016; *66* : 831-7.

21. Yadava DK, Hossain F, Choudhury PR, Kumar D, Singh AK. Biofortification of crops: A sustainable tool for nutritional security in India. *Indian Farming* 2018; *68* : 37-42.

22. Merah O. Genetic variability in glucosinolates in seed of *Brassica juncea*: Interest in mustard condiment. *J Chem* 2015; 606142.

23. Kumar V, Rani A, Shuaib M, Mittal P. Comparative assessment of trypsin inhibitor vis-à-vis Kunitz Trypsin Inhibitor and Bowman-Birk Inhibitor activities in soybean. *Food Anal Method* 2018; *11* : 2431-7.

24. Indiastat. Socio-economic statistical information about India. Available from: *https://www.indiastat.com/*, accessed on October 12, 2018.

25. Yadava DK, Choudhury PR, Hossain F, Kumar D. *Biofortified varieties: Sustainable way to alleviate malnutrition.* New Delhi: Indian Council of Agricultural Research; 2017.

26. Hossain F, Muthusamy V, Pandey N, Vishwakarma AK, Baveja A, Zunjare RU, *et al.* Marker-assisted introgression of *opaque2* allele for rapid conversion of elite hybrids into quality protein maize. *J Genet* 2018; *97* : 287-98.

27. Muthusamy V, Hossain F, Thirunavukkarasu N, Choudhary M, Saha S, Bhat JS, *et al.* Development of β-carotene rich maize hybrids through marker-assisted introgression of β-carotene hydroxylase allele. *PLoS One* 2014; *9* : e113583.

28. Finkelstein JL, Mehta S, Udipi SA, Ghugre PS, Luna SV, Wenger MJ, *et al.* A randomized trial of iron-biofortified pearl millet in school children in India. *J Nutr* 2015; *145* : 1576-81.

29. Sheftel J, Gannon BM, Davis CR, Tanumihardjo SA. Provitamin A-biofortified maize consumption increases serum xanthophylls and ^{13}C-natural abundance of retinol in Zambian children. *Exp Biol Med (Maywood)* 2017; *242* : 1508-14.

30. Palmer AC, Craft NE, Schulze KJ, Barffour M, Chileshe J, Siamusantu W, *et al.* Impact of biofortified maize consumption on serum carotenoid concentrations in Zambian children. *Eur J Clin Nutr* 2018; *72* : 301-3.

31. Gunaratna NS, De Groote H, Nestel P, Pixley KV, McCabe GP. A meta-analysis of community-level studies on quality protein maize. *Food Policy* 2010; *35* : 202-10.

32. Nuss ET, Tanumihardjo SA. Quality protein maize for Africa: Closing the protein inadequacy gap in vulnerable populations. *Adv Nutr* 2011; *2* : 217-24.

33. van Jaarsveld PJ, Faber M, Tanumihardjo SA, Nestel P, Lombard CJ, Benade AJ, *et al.* Beta-carotene-rich orange-fleshed sweet potato improves the Vitamin A status of primary school children assessed with the modified-relative-dose-response test. *Am J Clin Nutr* 2005; *81* : 1080-7.

34. Low JW, Arimond M, Osman N, Cunguara B, Zano F, Tschirley D, *et al.* A food-based approach introducing orange-fleshed sweet potatoes increased Vitamin A intake and serum retinol concentrations in young children in rural Mozambique. *J Nutr* 2007; *137* : 1320-7.

35. Paroda RS, Joshi PK, editors. *Proceedings of the national conference on sustainable development goals: India's preparedness and the role of agriculture.* New Delhi, India: Indian Council of Agricultural Research (ICAR), Trust for Advancement of Agricultural Sciences (TAAS) and International Food Policy Research Institute (IFPRI); 11-12 May, 2017. p. 48.

36. Gregory T, Sewando P. Determinants of the probability of adopting of Quality Protein Maize (QPM) technology in Tanzania: A logistic regression analysis. *Int J Dev Sustain* 2013; *2* : 729-46.

37. Zuma MK, Kolanisi U, Modi AT. The potential of integrating provitamin A-biofortified maize in smallholder farming systems to reduce malnourishment in South Africa. *Int J Environ Res Public Health* 2018; *15*. pii: E805.

38. Tessema M, Gunaratna NS, Donato K, Cohen JL, Connell M, Belayneh D, *et al*. Translating the impact of quality protein maize into improved nutritional status for Ethiopian children: study protocol for a randomized controlled trial. *BMC Nutr* 2016; *2* : 54.

39. Tanumihardjo SA, Ball AM, Kaliwile C, Pixley KV. The research and implementation continuum of biofortified sweet potato and maize in Africa. *Ann N Y Acad Sci* 2017; *1390* : 88-103.

40. Hellin J, Erenstein O. Maize poultry value chains in India: implications for research and development. *J New Seeds* 2009; *10* : 245-69.

41. Gupta HS, Hossain F, Muthusamy V. Biofortification of maize: An Indian perspective. *Indian J Genet Plant Breed* 2015; *75* : 1-22.

42. Neeraja CN, Ravindra BV, Ram S, Hossain F, Hariprasanna K, Rajpurohit BS, *et al*. Biofortification in cereals - Progress and prospects. *Curr Sci* 2017; *113* : 1050-7.

43. Dube N, Mashurabad PC, Hossain F, Pullakhandam R, Thingnganing L, Bharatraj DK, *et al.* Β-carotene bioaccessibility from biofortified maize (*Zea mays*) is related to its density and is negatively influenced by lutein and zeaxanthin. *Food Funct* 2018; *9* : 379-88.

44. Liu YQ, Davis CR, Schmaelzle ST, Rocheford T, Cook ME, Tanumihardjo SA, *et al.* β-cryptoxanthin biofortified maize (*Zea mays*) increases β-cryptoxanthin concentration and enhances the color of chicken egg yolk. *Poult Sci* 2012; *91* : 432-8.

45. PTI. M S Swaminathan: India must focus on nutrition security. Available from: *https://www.thehindubusinessline.com/economy/agri-business/m-s-swaminathanindia-must-focus-on-nutrition-security/article24739207.ece*, accessed on October 12, 2018.

For correspondence: Dr Trilochan Mohapatra, Indian Council of Agricultural Research, Ministry of Agriculture and Farmers Welfare, Government of India, Krishi Bhavan, New Delhi 110 001, India
e-mail: dg.icar@nic.in