

Shiv Kumar
Harsh Kumar Dikshit
Gyan Prakash Mishra
Akanksha Singh *Editors*

Biofortification of Staple Crops

 Springer

Biofortification of Staple Crops

Shiv Kumar • Harsh Kumar Dikshit •
Gyan Prakash Mishra • Akanksha Singh
Editors

Biofortification of Staple Crops

 Springer

Editors

Shiv Kumar
International Center for Agricultural
Research in the Dry Areas
Rabat, Morocco

Harsh Kumar Dikshit
Division of Genetics
ICAR-Indian Agricultural Research Institute
New Delhi, India

Gyan Prakash Mishra
Division of Genetics
ICAR-Indian Agricultural Research
Institute
New Delhi, India

Akanksha Singh
Amity Institute of Organic Agriculture
Amity University
Noida, Uttar Pradesh, India

ISBN 978-981-16-3279-2 ISBN 978-981-16-3280-8 (eBook)
<https://doi.org/10.1007/978-981-16-3280-8>

© Springer Nature Singapore Pte Ltd. 2022

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

The United Nations' Sustainable Development Goals (SDGs) target to end poverty, to protect the planet, and to ensure that all people enjoy peace and prosperity by 2030. The overarching challenge for the CGIAR scientific community is how to support countries to achieve SDGs by ensuring food and nutrition security to an ever-increasing population from limited and fast depleting resources under a climate crisis. Malnutrition is a serious global burden with ~800 million people being undernourished, over 2 billion suffering from micronutrient deficiencies, and more than a third of the adult population obese or overweight. Estimates indicate that over 60% of the world's 7 billion people are iron (Fe) deficient, over 30% are zinc (Zn) deficient, 30% are iodine (I) deficient, and more than 15% are selenium (Se) deficient, often causing health problems and development delays in those suffering from these deficiencies in spite of the fact that the global food production has increased manifold. Failure to link agricultural production with human nutrition and health has led to the development of unhealthy food systems. Biofortified crops, which have been bred to have higher amounts of micronutrients, can help provide these essential vitamins and minerals. They are effective in reducing hidden hunger caused by micronutrient deficiencies and are an integral component of food-based approaches to improve nutrition and food security.

Realizing the importance of micronutrients in human diets and their role in waning the hidden hunger among the poor masses, scientific community has recently placed major emphasis on biofortification of staple crops to augment the micronutrient availability with no cost at consumer end. Since 2003, the HarvestPlus program of CGIAR has added nutritional value into staple crops to address micronutrient deficiency among smallholder farming families and other low-resource populations. More than 50 million people in smallholder farming families in 41 countries now benefit from biofortified crops, which are making a measurable impact on human nutrition, health, and development. Presently, biofortified crops, including vitamin A orange sweet potato, iron beans, iron pearl millet, vitamin A yellow cassava, vitamin A orange maize, zinc rice, zinc wheat, and iron-rich lentils have been released in more than 30 countries. The technological advancement during the process has led to a great volume of research on trait discovery and deployment related to micronutrients in staple crops, and their bioavailability and efficacy in human health. Such efforts will further be augmented in the One CGIAR 2030 Research and

Innovation Strategy for achieving the SDGs by transforming food, land, and water systems under the genetic innovation to develop varieties with higher levels of vitamins and minerals that are adapted to a wide range of agro-ecological conditions and ensuring that the best germplasm for climate-adaptive and consumer-preferred traits continues to be used in breeding biofortified crops.

While the genetic diversity for micronutrient content in the existing germplasm is the basic need for mainstreaming biofortification in crop improvement program, community access to comprehensive information is key to further scientific efforts for developing nutrient-rich cultivars towards strengthening human health and nutrition efforts. However, information generated on various aspects of biofortification is scattered in different journals, and the researchers and scholars spend considerable time and energy in searching the relevant literature for their research and study. The present book '**Biofortification of Staple Crops**', which is a meticulously edited volume, is an attempt in this direction to bring together information on various aspects of biofortification and agronomic interventions. Twenty chapters in the book have been contributed by the renowned scientists whose research contributions on biofortification are acknowledged globally. I am quite hopeful that the information contained in this book will boost research efforts of plant scientists to bring about a major breakthrough in biofortification and will serve as a resource material for those who are involved in teaching, in research, and in technology scaling in agricultural crops. I congratulate the editors Drs. **Shiv Kumar, Harsh Kumar Dikshit, Gyan Prakash Mishra, and Akanksha Singh** for bringing out this book timely on such an important and emerging aspect and hope that it would be widely read by scholars and researchers.

ICARDA
Cairo, Egypt
February 22, 2021

Jacques Wery

Preface

Micronutrient deficiency is a leading global concern of public health importance. The root cause of this problem is non-availability of balanced diet to resource-poor communities. Resource poor rely on staple food for their energy requirement and these staple food crops are low in micronutrient concentration. Therefore, the biofortification of staple crops is essential to restrict malnutrition and diseases and promoting well-being of target population. Among the micronutrients, vitamin A, iron, and zinc are the most common deficiencies reported from economically disadvantaged communities posing detrimental effect on health and well-being of affected communities. Preschool children below the age of 5 years and women of reproductive age are most affected by micronutrient deficiencies.

Globally 50% deaths of under-5 years are associated with vitamin A, zinc, and iron deficiency. Vitamin A deficiency causes night blindness, child morbidity, and mortality. Iron deficiency causes anaemia, maternal and childhood deaths, and poor cognitive development. Nearly 60% global population suffers from iron deficiency. Zinc deficiency causes reduction in linear growth, diarrhoea, and impaired immunity among 30% of global population. The acute deficiency of vitamin A, Fe, and Zn causes childhood stunting. The stunted children exhibit poor cognitive development and have risk of developing cardiovascular diseases, obesity, and type 2 diabetes. It is estimated that globally the decline in productivity due to loss of cognitive skills, stunting, and chronic diseases is likely to cost \$35 trillion by 2030.

The United Nation's Sustainable Development Goals (SDGs) SDG 2 and SDG 3 focus on eradication of micronutrient deficiencies. National Research Programmes are joining hands with CGIAR institutes to achieve SDGs ensuring food and nutritional security for all. Biofortified crops with relatively higher micronutrient concentration are sustainable means to address micronutrient deficiency for resource-poor communities. The limited efficacy studies conducted have indicated their role in improving micronutrient availability. The joint efforts of HarvestPlus programme and National Research Programmes have led to development and dissemination of biofortified varieties of different crops in different countries. Biofortified crops have been developed in wheat, rice, maize, pearl millet, cassava, sugar beet, dry beans, lentil, and several other crops benefitting nearly 50 million people in small farming families.

The current book “**Biofortification of Staple Crops**” compiles research and technological advances made in evaluation of genetic resources, gene discovery, product development, bioavailability, and efficacy studies for different crops. The twenty chapters included have been compiled by leading scientists working on biofortification of respective crops. The editors are hopeful that compiled information will serve as basic resource material for teachers, students, and researchers and proliferate the productivity and impact of biofortification.

Rabat, Morocco
New Delhi, India
New Delhi, India
Noida, Uttar Pradesh, India

Shiv Kumar
Harsh Kumar Dikshit
Gyan Prakash Mishra
Akanksha Singh

Acknowledgements

The editorial team expresses sincere thanks to all the contributors for their valuable contribution, dedication, patience, and efficiency. Editing a multi-author book is a tedious task. However, in this case it was encouraging and a learning experience. All authors and co-authors responded promptly with consequence that the manuscripts were delivered on time without any difficulty. This helped editors in preparing the final text for publisher timely.

Editors convey deep gratitude to all who have rendered invaluable assistance in making this publication possible. Authors express their gratitude to Dr. Jacques Wery, Deputy Director General—Research, ICARDA, and Dr. A.K. Singh, Director, ICAR-IARI, for all support for completion of this book. Lastly, we thank Springer Nature for publishing this book.

Contents

| | | |
|----------|---|------------|
| 1 | Biofortification of Staple Crops: Present Status and Future Strategies | 1 |
| | Shiv Kumar, Harsh Kumar Dikshit, Gyan P. Mishra, Akanksha Singh, M. Aski, and P. S. Virk | |
| 2 | Historical Overview of Biofortification in Crop Plants and Its Implications | 31 |
| | Gyan P. Mishra, Harsh Kumar Dikshit, Priti, Bharti Kukreja, M. Aski, D. K. Yadava, Ashutosh Sarker, and Shiv Kumar | |
| 3 | Genetic Fortification of Rice to Address Hidden Hunger: Progress and Prospects | 63 |
| | Haritha Bollinedi, A. K. Singh, K. K. Vinod, S. Gopala Krishnan, Prem Chand Gyani, P. K. Bhowmick, M. Nagarajan, and R. K. Ellur | |
| 4 | Advances in Wheat Biofortification and Mainstreaming Grain Zinc in CIMMYT Wheat Breeding | 105 |
| | Govindan Velu, Ravi P. Singh, Arun K. Joshi, and Parminder Virk | |
| 5 | Barley Biofortification | 119 |
| | Dinesh Kumar, Sneha Narwal, and Ramesh Pal Singh Verma | |
| 6 | Biofortification of Maize for Nutritional Security | 147 |
| | Firoz Hossain, Rajkumar U. Zunjare, Vignesh Muthusamy, Jayant S. Bhat, Brijesh K. Mehta, Devender Sharma, Zahirul A. Talukder, Rashmi Chhabra, Ashvinkumar Katral, Suman Dutta, Gulab Chand, Vinay Bhatt, Subhra J. Mishra, Nisrita Gain, Ravindra Kasana, Gopinath Ikkurtti, and Hriipulou Duo | |
| 7 | Pearl Millet: Biofortification Approaches in a Micronutrient Dense, Climate-Resilient Nutri-Cereal | 175 |
| | Rakesh K. Srivastava, C. Tara Satyavathi, Ram B. Singh, S. Mukesh Sankar, Sumer P. Singh, S. L. Soumya, and Chandan Kapoor | |

| | | |
|-----------|--|------------|
| 8 | Biofortifying Sorghum for Delivering Grain Micronutrients in High Yielding Cultivars with Market-Preferred Traits | 195 |
| | A. Ashok Kumar, Shivaji P. Mehtre, Gaddameedi Anil, Sunita Gorthy, Kotla Anuradha, Rahul M. Phuke, Jayakumar Jaganathan, Hari Prasanna, Sharad Rao Gadakh, Uttam Chavan, H. V. Kalpande, and Vilas A. Tonapi | |
| 9 | Pulse Crop Biofortification Toward Human Health, Targeting Prebiotic Carbohydrates, Protein, and Minerals | 205 |
| | Dil Thavarajah, Sarah Powers, George Vandermark, Casey R. Johnson, Emerson Shipe, and Pushparajah Thavarajah | |
| 10 | Dry Bean Biofortification with Iron and Zinc | 225 |
| | Karen Cichy, Christina Chiu, Krista Isaacs, and Raymond Glahn | |
| 11 | Lentil Biofortification | 271 |
| | Harsh Kumar Dikshit, Gyan P. Mishra, M. Aski, Akanksha Singh, P. S. Virk, and Shiv Kumar | |
| 12 | Biofortification of Mungbean | 295 |
| | Aditya Pratap, Inderpreet Dhaliwal, Chandra Mohan Singh, A. Mahalingam, N. Manivannan, T. Basavaraja, Meenal Rathore, Yogendra Singh, Pravin Tiwari, Sunit Yadav, and Ayushi Tripathi | |
| 13 | Biofortification of Chickpea | 335 |
| | Shailesh Tripathi, Rajesh Kumar Singh, Swarup K. Parida, S. K. Chaturvedi, and P. M. Gaur | |
| 14 | Prospects of Biofortification in Groundnut Using Modern Breeding Approaches | 345 |
| | Sai Rekha Kadirimangalam, Rachana Bagudam, Murali T. Variath, and Janila Pasupuleti | |
| 15 | Vegetable Biofortification: An Underexploited Silver Lining for Malnutrition Management | 379 |
| | Jagdish Singh, Jyoti Devi, and Vidya Sagar | |
| 16 | Biofortification of Cassava: Recent Progress and Challenges Facing the Future | 417 |
| | Richard T. Sayre | |
| 17 | Transgenics for Biofortification with Special Reference to Rice | 439 |
| | Shuvobrata Majumder, Karabi Datta, and Swapan Kumar Datta | |

| | | |
|-----------|--|------------|
| 18 | Agronomic and Transgenic Approaches for Rice Zn Biofortification | 461 |
| | Raul Antonio Sperotto, Bruno Bachiega Navarro, Jover da Silva Alves, Pedro Vinicius da Cruz Dias, Ana Catarina Oliveira Tavares, Gustavo Brunetto, and Felipe Klein Ricachenevsky | |
| 19 | Agronomic Approaches for Biofortification of Staple Food Crops | 483 |
| | Somanath Nayak, Sunil Mandi, Kirttiranjan Baral, Radha Prasanna, and Yashbir Singh Shivay | |
| 20 | Micronutrients: Soil to Seed | 519 |
| | Neha Gupta, Hari Ram, and Ismail Cakmak | |

About the Editors

Shiv Kumar leads ICARDA's Food Legumes Program delivering improved germplasm of lentil, kabuli chickpea, faba bean, and grass pea to national partners in South Asia, Sub-Saharan Africa, West Asia, and North Africa. He works on developing short-duration, climate-smart varieties of lentil and grass pea, with high iron and zinc content for the sustainable intensification of cereal-based cropping systems. During his three-decade career, he has worked with national and international partners to develop 39 lentil, 5 mung bean, 2 urdbean, 1 rice, and 3 grass pea varieties. He has published 196 peer-reviewed journal articles, 77 book chapters, 10 books, 7 technical bulletins, and 2 training manuals. He also supervises teaching and training of national partners. He has done his master's and PhD in plant breeding from G.B.P.U.A. & T., Pantnagar (India).

Harsh Kumar Dikshit is serving as principal scientist at ICAR-Indian Agricultural Research Institute, New Delhi (India). He is working on genetic improvement of grain legumes through conventional and molecular approaches. He has developed 15 varieties of different grain legumes (lentil, mung bean, and dry beans) for cultivation in India. His present focus is on basic and applied research on biofortification and biotic stresses of lentil and mung bean. He is faculty of Division of Genetics and is involved in teaching of different courses and thesis research guidance to postgraduate students. He has done his master's and PhD in plant breeding from G.B.P.U.A. & T., Pantnagar (India).

Gyan Prakash Mishra is currently working as principal scientist at ICAR-Indian Agricultural Research Institute, New Delhi (India). Before that he has worked at DRDO-Defence Institute of High Altitude Research, Leh (India), as Scientist 'C' and at ICAR-Directorate of Groundnut Research, Junagadh (India), and ICAR-Indian Institute of Vegetable Research, Varanasi (India), as senior scientist. His major research interest includes crop improvement through conventional, molecular, and transgenics approaches. He has done his master's and PhD in genetics from Indian Agricultural Research Institute, New Delhi (India), and postdoc from University of California, Riverside, and Purdue University, USA, as BOYSCAST-Fellow.

Akanksha Singh is working as assistant professor at Amity Institute of Organic Agriculture, Amity University, Noida (India). Her research areas include characterization of Lens species for grain Fe and Zn and association mapping and development of genetic and genomic resources. She has published around 23 research papers in reputed journals. She has contributed to the development of lentil varieties for central India and registration of biofortified lentil germplasm L 4704 (Fe and Zn rich). She received Babu Jag Jivan Ram Memorial Gold Medal and Chancellor's Silver Medal from Bundelkhand University, Jhansi, for her master's degree. She has done PhD in biotechnology from Banasthali University, Banasthali (India).



Biofortification of Staple Crops: Present Status and Future Strategies

1

Shiv Kumar, Harsh Kumar Dikshit, Gyan P. Mishra, Akanksha Singh, M. Aski, and P. S. Virk

Abstract

Micronutrient deficiencies affect nearly one-third of global population. Biofortification of staple crops is considered as a long-term and sustainable approach to ameliorate micronutrient deficiencies. The review summarizes the need for biofortification, conventional breeding, genetic variation for micronutrient concentration of different crops, quantitative trait loci identified in different crops for micronutrient concentration, transgenic approach, status of release of biofortified crop varieties and efficacy of biofortified crop varieties. Research efforts focus on increasing both micronutrient concentration and bioavailability. Key challenges (mainstreaming biofortification, building consumer demand and integration of biofortification in policies, programs and investments) have been briefly highlighted. The achievements made in the biofortification of staple crops are very promising and raise hope for nutritional security for all.

Keywords

Biofortification strategies · Biofortification · Micronutrient bioavailability · Staple crop biofortification · Biofortification status

S. Kumar (✉)

Biodiversity and Crop Improvement Program, ICARDA, Rabat, Morocco

e-mail: sk.agrawal@cgiar.org

H. K. Dikshit · G. P. Mishra · M. Aski

Division of Genetics, ICAR-Indian Agricultural Research Institute, New Delhi, India

A. Singh

Amity Institute of Organic Agriculture, Amity University, Uttar Pradesh, Noida, India

P. S. Virk

HarvestPlus, ICRISAT, Patancheru, India

© Springer Nature Singapore Pte Ltd. 2022

S. Kumar et al. (eds.), *Biofortification of Staple Crops*,

https://doi.org/10.1007/978-981-16-3280-8_1

1 Introduction

The global population is expected to reach 9.8 billion by 2050 (<https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html>). High yielding varieties with better nutritive value are required to meet the nutritional demands of this population. Nutritive diet is not affordable and accessible to all and 820 million people face food shortage with undernutrition affecting 10.8% global population (FAO, IFAD, UNICEF, WFP and WHO 2019). The term micronutrient includes vitamins and micronutrients required from diet for maintenance of normal molecular and cellular function. Micronutrient deficiencies (MND) are a major concern in developing countries with poor access to healthcare due to a lack of resources and medical staff. Preschool children below the age of 5 years and women of reproductive age are most affected by MND (Nestel et al. 2006; Bailey et al. 2015). MND results in poor health reducing educational attainments, work capacity and earnings (Bailey et al. 2015). MNDs affecting individuals have an adverse effect on human capital and economic development of the country. Iron is part of haemoglobin and myoglobin and is involved in transport and storage of oxygen. Iron is a component of electron transport particles, ribonucleotide reductase enzyme system and functions as a catalyst in the production of free radicals.

Iron deficiency is a common cause of anaemia. It affects 43% of preschool children and 38% of pregnant women (WHO 2015). During pregnancy, iron is required for expansion of erythrocyte mass, plasma volume and foetal placenta growth (Scholl 2005). More than 2 billion people are anaemic due to Fe deficiency. Iron deficiency during pregnancy results in maternal anaemia and reduced new borne iron store. Iron deficiency can result in impairment of cognitive function, growth retardation and low productivity. The assessment of iron status is based on plasma ferritin concentrations at $\geq 30 \mu\text{g/L}$ (iron sufficiency), 15 to $<30 \mu\text{g/L}$ (modest iron depletion) and $<15 \mu\text{g/L}$ (severe iron depletion) (Loy et al. 2019).

Zinc is an important micronutrient playing a critical role in gene expression and cell development and division (Hambridge 2000). Zinc is reported from all fluids and body tissues. Zinc is a component of 300 enzymes regulating protein, nucleic acid lipid and carbohydrate synthesis and degradation. Zinc maintains cell and organ integrity by stabilizing cellular membrane and components. Zinc plays a key role in polynucleotide transcription. Zinc content of average human body is estimated as 30 mmol (2 g). Zinc is vital for immune system as it affects cellular and humoral immune response (Hojyo and Fukada 2016). Stunting is very common in preschool children. Stunting affects more than 250,000 preschool children. Zinc deficiency can contribute to stunting, as it restricts growth and decreases resistance to infections (Prasad 2013). Zinc deficiency results in growth retardation, diarrhoea, delayed sexual and bone maturation, skin lesions and impaired appetite (Hambridge 1987).

Selenium is associated with thyroid hormone metabolism, antioxidant defence system and oxidative metabolism and immune system (Fairweather-Tait et al. 2011). Selenium deficiency causes thyroid dysfunction, cardiovascular disasters, the spread of viruses or tumour disorders (Tamas 2000) and reduces sperm viability (Rayman 2002). The studies of Rayman (2012) have associated Se deficiency with Down's

syndrome and congenital hypothyroidism. Endemic cardiomyopathy (Keshan disease) was recorded in Se-deficient regions in Keshan County, China. Keshan disease is a heart disorder connected with cardiogenic shock and/or congestive heart failure. Another disease reported from Se-deficient regions in the world is Kashin Beck disease (degenerative osteoarthropathy).

Vitamin A is crucial for visual function, tissue differentiation, organogenesis and immune response (Sommers 1995). Vitamin A deficiency causes night blindness and increases the risk of disease and mortality from infections (WHO 2014; Stevens et al. 2015). Vitamin A deficiency may also occur due to malabsorption and liver diseases (Rosen et al. 2015). Serum retinol below 0.70 $\mu\text{M/L}$ indicates vitamin A deficiency. Early symptoms of vitamin A (hemeralopia and xerophthalmia) are often overlooked. Severe deficiency results in impairment of mucosae, sensory organs, bone marrow, skin endocrine and immune systems (Balint 1998). Severe prevalence of vitamin A deficiency among children of 6–59 months in Asia and Africa has been reviewed by Stevens et al. (2015).

Iodine is constituent of thyroxine (T4), triiodothyronine (T3) and thyroid hormones and is required for development, growth and metabolism from pregnancy, infancy to throughout life (FAO/WHO 2005; WHO/UNICEF/ICCIDD 2008). Iodine deficiency during pregnancy and childhood can cause mental retardation due to impaired growth and brain development. Zimmermann and Andersson (2012) reported iodine deficiency in 29.8% of school children. Iodine deficiency causes cretinism and goitre, mental retardation, hypothyroidism, prenatal death, infant mortality and decreased fertility (WHO/UNICEF/ICCIDD 2008). Foliates are necessary for methylation cycle and biosynthesis of pyrimidines and purines (Scott et al. 2000). Folate deficiency results in the reduction of capacity to synthesize DNA and rate of cell division. Anaemia is caused due to reduction in biosynthesis of cells in the bone marrow. Neural tube defects have been reported in children of women deficient in folates in first 28 days after conception (March of Dimes 2006).

Dietary diversification, supplementation, fortification and biofortification are being used for reducing the MNDs. Biofortification is the process of increasing vitamin and mineral density in a crop through conventional plant breeding, transgenic approach or agronomic practices. The regular consumption of staple biofortified crops produces measurable improvement in human nutrition and health. The main reason for micronutrient deficiencies in developing countries is poverty. Due to lack of resources people rely on staple crops to meet their energy requirements. Animal products, protein rich food, vegetables and fruits are not part of regular diet. Areas low in soil bioavailable micronutrients produce grains low in micronutrients (Vanlauwe et al. 2015).

The plasma and tissue micronutrient concentration reflects the dietary intake. Inflammation and infection can alter the partitioning of micronutrients in the body (Thurnham and Northrop-Clewes 2016). To identify infection, C-creative protein (CRP) and α 1-acid glycoprotein (AGP) tests (Thurnham et al. 2015) are routinely conducted following the methodology appropriate for each micronutrient. Intestinal infection caused by helminthosporium affects nutritional status by reducing micronutrient absorption and increasing anaemia risk due to worm feeding on blood and

causing loss of appetite (Chaparro and Suchdev 2019). Supplementation is another strategy to address MND. Vitamin A and zinc supplementation have been successful (Black et al. 2008). Global initiative on vitamin A has prevented 1.25 million deaths (WHO 2018). Supplementation requires access to medical facilities and education for compliance (Bailey et al. 2015). Storage and calibration of supply vs. demand are very important for supplementation. Supplementation programme addresses few micronutrients only and does not address the poor-quality diet. Food fortification is another option of reducing MND. Fortification of salt with iodine, sugar and cooking oil with vitamin A and flour, dairy food, condiments, sugar and salt with iron is common practice (Bouis et al. 2017). In China, selenium-fortified salt and tea is being used against Keshan disease (Combs 2000). Folic acid-fortified wheat and maize is used to avoid neural tube defect caused due to folate deficiency (Centeno Tablante et al. 2019).

1.1 Advantages of Biofortification

During the last 60 years, agricultural research in developing countries has focussed on increasing the production and improving the availability of calorically dense staple crops. Similar efforts were not made for increasing the availability of micro-nutrient rich pulses, vegetables and consequently their prices have increased and these are not affordable to resource poor. Increased availability of biofortified crops and dietary diversification are vital for addressing the MND. Complementation of biofortification with supplementation and industrial fortification can alleviate MND. Biofortification is cost-effective and even resource poor can avail the benefits at marginal cost.

Biofortified varieties once developed can be evaluated for adaptation in new environments and geographies. Biofortification needs to be mainstreamed as a core breeding objective by international and national crop development programmes. Biofortified crops can be utilized by resource poor having no access to the diversified diet. The target micronutrient levels can meet the nutritional requirements of children and women. According to Hoddinott et al. (2013) benefit of US \$17 may be gained for every dollar invested in biofortification. Cost-effectiveness of any intervention is based on crop, micronutrient and country. Supplements and industrialized fortified food provide a higher level of vitamins and minerals and biofortified crops ensure daily adequacy of micronutrients throughout the life.

2 Conventional Breeding

Crop biofortification is a multidisciplinary approach involving plant breeders, nutritionists and food technologists. Using conventional breeding the nutrient levels of staple crops can be increased to the target level without altering the agronomic traits and compromising yield levels. The steps in the development of micronutrient

dense varieties include the screening of primary and secondary gene pool, pre-breeding and breeding for development of micronutrient dense lines and their testing at multilocation to assess $G \times E$ interactions (influence of environment on micronutrient expression). Breeding targets for each micronutrient is based on the consumption pattern of target population, nutrient bioavailability and losses during processing and storage.

Exploration of available genetic diversity (primary and secondary gene pool) for micronutrient concentration is the first step in crop improvements. Along with micronutrient concentration screening is also carried out for agronomic traits (yield, seed size, maturity duration, disease and insect resistance, etc.). The suitable genotypes identified are utilized in the hybridization programme for the development of mapping population for genetic and molecular studies and breeding material. Molecular markers have been identified in different crops linked to grain Fe, Zn and Se concentration using biparental or association mapping approach. Mapping populations, and markers identified for grain Fe, Zn and Se concentration in different crops are presented in Table 1.1. Molecular markers linked to micronutrients can facilitate in marker-assisted selection. The breeding material can be advanced rapidly by using off-season nursery and speed breeding. The existing varieties, pre varieties and finished germplasm products can be fast tracked to ensure their early delivery. Pre breeding is necessary when unadapted sources are used as donor in breeding programmes. Product enhancement activities and pre breeding are simultaneously carried out by most breeders. The micronutrient concentration, yield and resistance to biotic and abiotic stresses of the developed products can be assessed in multilocation trials (study of $G \times E$ interactions). The promising varieties identified are then tested in multiseason and multilocation trials for agronomic performance by national government agencies for release and notification.

2.1 Genetic Variation for Micronutrient Concentration

The genetic variation for micronutrient concentration has been studied in different crops. The most important sources include landraces, primitive cultivars and wild relatives. Fe range of 4–30 mg/kg and Zn range of 8–95 mg/kg, seed was reported by Yang et al. (1998) in rice. Gregorio et al. (2000) studied the core collection of brown rice and report Fe and Zn ranges of 6–24 and 14–58 mg/kg, respectively. Banerjee et al. (2010) reported Fe range of 4.8–22.7 mg/kg and Zn range of 13.95–41.73 mg/kg from the study of 46 rice accessions. Anuradha et al. (2012) evaluated 122 brown rice accessions and reported 6.2–71.6 mg/kg as a range for Fe. Jahan et al. (2013) reported a very high range (1.32–100.45 mg/kg) for Fe.

Wheat has been extensively studied for grain Fe and Zn concentration. Fe concentration range of 25–73 mg/kg and Zn concentration range of 25–92 mg/kg have been reported by Monasterio and Graham (2000). Clarke et al. (2002) reported similar range in durum wheat. Graham et al. (1999), Cakmak et al. (2000) and Bálint et al. (2001) studied wild relatives of wheat and reported higher Fe and Zn concentration in comparison to cultivated wheat. Hentschel et al. (2002) reported total

Table 1.1 Mapping populations, and markers identified for grain Fe, Zn and Se concentration in different crops

| Crop | Population/lines/ cultivars/accession | No. of markers identified | | | Reference |
|----------|--|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| | | Identified for grain Fe conc. | Identified for grain Zn conc. | Identified for grain Se conc. | |
| Wheat | DH/Hanxuan 10 × Lumai 14 | | 4 QTLs | | Shi et al. (2008) |
| | DH/RAC875-2 × Cascades | | 4 QTLs | | Genc et al. (2009) |
| | RIL/Langdon × G18-6 | 11 QTLs | 6 QTLs | | Peleg et al. (2009) |
| | RIL/Tb5088 × Tm14087 | 3 QTLs | 2 QTLs | | Tiwari et al. (2009) |
| | RIL/Xiaoyan 54 × Jing 411 | 2 QTLs | 2 QTLs | | Xu et al. (2012) |
| | RIL/Tabassi × Taifun | 6 QTLs | 2 QTLs | | Roshanzamir et al. (2013) |
| | DH/Hanxuan × Lumai 14 | 4 QTLs | | | Shi et al. (2013) |
| | RIL/PBW343 × Kenya Swara | | 3 QTLs | | Hao et al. (2014) |
| | RIL/SHW-L1 × Chuanmai 32 | 4 QTLs | 4 QTLs | 4 QTLs | Pu et al. (2014) |
| | RIL/P 1348449 × HUW 234 | 5 QTLs | 5 QTLs | | Srinivasa et al. (2014) |
| | DH/Berkut × Krichauff | 1 QTL | 2 QTLs | | Tiwari et al. (2016) |
| | RIL/SeriM82 × SHW CWI76364 | 10 QTLs | 3 QTLs | | Crespo- Herrera et al. (2016) |
| | RIL/Louries × Bateleur | 9 QTLs | 12 QTLs | | Crespo- Herrera et al. (2017) |
| | RIL/Bubo × Turtur | 3 QTLs | 4 QTLs | | Crespo- Herrera et al. (2017) |
| | F2/WTSD91 × WN-64 | 3 QTLs | 3 QTLs | | Hussain et al. (2017) |
| | RIL/WH542 × PI94624 | 1 QTL | 1 QTL | | Krishnappa et al. (2017) |
| | RIL/Adana99 × 70711 | 8 QTLs | 10 QTLs | | Velu et al. (2017) |
| | RIL/TN18 × LM 6 | | | 7 QTLs | Wang et al. (2017) |
| AM panel | 3 QTLs | 3 QTLs | | Gorafi et al. (2018) | |

(continued)

Table 1.1 (continued)

| Crop | Population/lines/ cultivars/accession | No. of markers identified | | | Reference |
|--|--|-------------------------------------|-------------------------------------|--|--------------------------------------|
| | | Identified for grain Fe conc. | Identified for grain Zn conc. | Identified for grain Se conc. | |
| | RIL/SHW-L1 × Chuanmai 32 | | | 24 QTLs | Pu et al. (2018) |
| | AM panel | | 2 QTLs | | Velu et al. (2018) |
| | RIL/Langdon × G 18-16 | | | 15 QTLs | Yan et al. (2018) |
| Rice | DH/IR64 × Azucena | 3 QTLs | 3 QTLs | | Stangoulis et al. (2007) |
| | RIL/Zhenshan 97 × Minghui 63 | 2 QTLs | 3 QTLs | | Lu et al. (2008) |
| | BIL/Teqing × <i>O. rufipogon</i> | 1 QTLs | 3 QTLs | | Garcia- Oliveira et al. (2009) |
| | Sasanishiki × Habataki | – | 1 QTL | | Ishikawa et al. (2010) |
| | RIL/Bala × Azucena | 4 QTLs | 1 QTL | | Norton et al. (2010) |
| | DH/Zy08 × JX17 | | 2 QTLs | | Zhang et al. (2011) |
| | RIL/Madhukar × Swarna | 2 QTLs | 4 QTLs | | Anuradha et al. (2012) |
| | F2/PAU × Palman 579 | 8 QTLs | 3 QTLs | | Kumar et al. (2014) |
| | AM panel | 13 SSRs | 2 SSRs | | Nawaz et al. (2015) |
| | RIL/Swarna × Moroberekan | 1 QTL | | | Indurkar et al. (2015) |
| | BILs/Ce258 × IR 75862 ZGX1 × IR 75862 | 1 QTL | 4 QTLs | | Xu et al. (2015) |
| | BILs/ <i>O. sativa</i> × <i>O. rufipogon</i> | 3 QTLs | 6 QTLs | | Hu et al. (2016) |
| | BRILs/Nipponbare × W 1627 | | 4 QTLs | | Ishikawa et al. (2017) |
| | BC2F2/Swarna × <i>O. nivara</i> | 5 QTLs | 3 QTLs | | Swamy et al. (2018) |
| | DH/PSBRc 82 × Joryeongbyes PSBc × IR 69428 | 8 QTLs | 1 QTL | | Swami et al. (2018) |
| DU/IR 64 × IR 69428 BR29 × IR 75862 | | 8 QTLs | | Descalsota- Empleo et al. (2019) | |

(continued)

Table 1.1 (continued)

| Crop | Population/lines/ cultivars/accession | No. of markers identified | | | Reference |
|-----------------|---|-------------------------------------|-------------------------------------|-------------------------------------|----------------------------|
| | | Identified for grain Fe conc. | Identified for grain Zn conc. | Identified for grain Se conc. | |
| | BC2F5/RP-Bio226 × Sampada | 2 QTLs | 3 QTLs | | Dixit et al. (2019) |
| | F4/PAU 201 × Palman | 5 QTLs | 1 QTL | | Kumar et al. (2019) |
| | AM panel | 7 QTLs | 5 QTLs | | Bollinedi et al. (2020) |
| | DH/IR05F102 × IR69428 | 5 QTLs | 5 QTLs | | Calayugan et al. (2020) |
| | DH/Hwaseonchal × Goami 2 | 1 QTL | 1 QTL | | Jeong et al. (2020) |
| | AM panel | 2 QTLs | 3 QTLs | | Pradhan et al. (2020) |
| Pearlmillet | RIL/ICMS 8511-S1- 17-2-1-1-B-P03 × AIMP 92901-S1-183- 2-2-B-08 | 11 QTLs | 8QTLs | | Kumar et al. (2018) |
| | RIL/ICMB 841-P3 × 863B-P2 | 2 QTLs | 2 QTLs | | Kumar et al. (2016) |
| Maize | F 2:3/178 × P53 | 1 QTL | 4 QTLs | | Jin et al. (2013) |
| | RIL/B84 × Os6-2 | 3 QTLs | 3 QTLs | | Šimić et al. (2012) |
| Sorghum | RIL/296B × PVK 801 | 3 QTLs | 3 QTLs | | Kotla et al. (2019) |
| Chickpea | AM panel | 4 SNP | 5 SNPs | | Diapari et al. (2014) |
| | RIL/ICC 4958 × ICC 8261 | 8 QTLs | 8 QTLs | | Upadhyaya et al. (2016) |
| Lentil | AM panel | 2 SNPs | 1 SNP | | Khazaei et al. (2017) |
| | AM panel | 4 SSRs | 3 SSRs | | Singh et al. (2017) |
| | AM panel | 2 SSRs | 3 SSRs | | Kumar et al. (2018) |
| Common beans | RIL/AND 696 × GI 9833 | 1 QTL | 1 QTL | | Cichy et al. (2009) |
| | RIL/DOR 363 × GI 9833 | 13 QTLs | 13 QTLs | | Blair et al. (2010) |
| | AM panel | 6 SNPs | 6 SNPs | | Katuramu et al. (2018) |
| | 7 populations | 12 meta QTLs | | | Izquierdo et al. (2018) |

(continued)

Table 1.1 (continued)

| Crop | Population/lines/ cultivars/accession | No. of markers identified | | | Reference |
|---------|--|-------------------------------------|-------------------------------------|-------------------------------------|--------------------------|
| | | Identified for grain Fe conc. | Identified for grain Zn conc. | Identified for grain Se conc. | |
| Pea | AM panel | 1 EST SSR | – | | Kwon et al. (2012) |
| | AM panel | 9 SNPs | 2 SNPs | | Diapari et al. (2015) |
| Soybean | F2:4 lines/Anoka × A7 | 2 genes | – | | Peiffer et al. (2012) |
| | – | 1 QTLs | – | | King et al. (2013) |

carotenoids content of 200 µg/100 g for four wheat varieties. Cakmak et al. (2004) reported Fe range of 14–190 mg/kg and Zn range of 15–109 mg/kg. They reported that wild species are an important source for increasing Fe and Zn concentration in wheat grains. Hidalgo et al. (2006) reported carotenoids content of 54 cultivars of Einkorn wheat, 6 durum wheat varieties and 5 bread wheat cultivars and reported carotenoids concentration of 320 µg/100 g, 195 µg/100 g and 841 µg/100 g, respectively. Morgounov et al. (2007) studied 60 germplasm lines and reported Fe range of 25–56 mg/kg and Zn range of 20–39 mg/kg. Velu et al. (2011) recorded 25–56 mg/kg Fe and 26–65 mg/kg Zn in wheat accessions. They reported that the genotypes with high level of micronutrients were unadapted with low yield level. Badakhshan et al. (2013) studied 81 cultivars of bread wheat and reported Fe range of 41.4–67.7 mg/kg and Zn range of 36.4–73.8 mg/kg. Goel et al. (2018) studied wheat landraces of India and reported modest Fe range of 32.7–54.5 mg/kg and Zn range of 15.8–66 mg/kg. Khokhar et al. (2020) reported Zn range of 24–49 mg/kg from the study of 245 landraces.

Pearl millet is a rich source of micronutrients among the cereals. The variation for grain Fe (31–61 mg/kg) and Zn (32–54 mg/kg) in pearl millet has been reported by Velu et al. (2007), Gupta et al. (2009), Govindaraj et al. (2013) and Rai et al. (2013). Pucher et al. (2014) evaluated 72 pearl millet accessions from West and Central Africa in Niger and reported Fe range of 24.2–48.8 and Zn range of 19.8–43.4 mg/kg. Evaluation of 225 pearl millet accessions in Sudan (Bashir et al. 2014) revealed Fe range of 19.7–86.4 mg/kg and Zn range of 13.5–82.4 mg/kg. Carotenoids in the range of 0.5–3.4 µg/g for maize hybrids has been reported by Egesel et al. (2003) and range of 0.7–4.7 µg/g for kernel β-carotene has been reported by Menkir et al. (2008). Kernel β-carotene range of 0.01–1.72 µg/g for a set of Chinese maize inbreds has been reported by Chander et al. (2008). Prasanna et al. (2011) reported kernel Fe range of 11.28–60.4 mg/kg and Zn range of 15.14–52.95 in maize kernel. Queiroz et al. (2011) reported Fe range of 12.2–36.7 mg/kg and Zn range of 17.5–42 mg/kg by evaluating 22 diverse tropical inbreds. Vignesh et al. (2012) reported range of 0.02–16.50 µg/g for kernel β-carotene for 105 diverse maize inbreds.

Ma et al. (2004) estimated Fe range of 21–83 mg/kg in the barley core collection. In sorghum, Reddy et al. (2005) reported Fe in the range of 20–37 mg/kg and Zn in the range of 13–31 mg/kg. Islam et al. (2002) reported Fe range of 35–92 mg/kg and Zn range of 21–59 mg/kg in beans. Fe range of 48–74 mg/kg and Zn range of 17–28 mg/kg in beans were reported by Ariza-Nieto et al. (2007). A wide range of variability for grain Fe and Zn concentration in lentil has been estimated by Singh et al. (2017). Fe concentration in lentil seed varied from 34.4–119.5 mg/kg seed and Zn from 12.3–78.75 mg/kg seed.

3 Transgenic Approach

In crops with low diversity for the desired micronutrient in gene pool, transgenic approach is a viable option for producing biofortified varieties possessing desired concentration of micronutrient and agronomic traits. Rice has been improved for vitamin A using daffodil *Phytoene synthase* and *Erwinia uredovora phytoene desaturase* (Ye et al. 2000), maize *phytoene synthase* (Paine et al. 2005) and *daffodil phytoene synthase* and *lycopene β -cyclase* (Beyer et al. 2002). Fe biofortification in rice has been reported using overexpression of soybean *ferritin gene Soyfer H-1* (Goto et al. 1999), *phaseolus ferritin* (Lucca et al. 2001), *ferritin* (Masuda et al. 2012, 2013) and *OsNAS2* (Johnson et al. 2011). Zn enhancement in rice has been carried out using barley *HvNAS1* gene (Masuda et al. 2009), soybean *ferritin*, *Aspergillus flavus phytase*, *OsNAS1* (Wirth et al. 2009) and *OsNAS2* (Johnson et al. 2011). Vitamin A biofortification in wheat has been reported by Cong et al. (2009) (maize *psy1* gene encoding *phytoene synthase*, *bacterial crtI*) and Wang et al. (2014) (*CrtB* or *CrtI*).

Wheat biofortification for Fe was reported by Drakakaki et al. (2000) (soybean *ferritin*) and Borg et al. (2012) (overexpression of *TaFer1-A*). In maize vitamin A-rich transgenics have been produced using bacterial *crtB* and *crtI* (Aluru et al. 2008) and maize *psy1* (Naqvi et al. 2009). In cassava, Welsch et al. (2010) reported the development of vitamin A-rich transgenic using bacterial *crtB*. Ravanello et al. (2003) developed vitamin A-rich canola using *crtB* and *crtI*. Transgenic varieties possess great potential but their release for cultivation depends on approval for national biosafety and regulatory processes. The release of golden rice is delayed due to highly risk averse regulatory approval processes (Wesseler and Zilberman 2014). Golden rice has been approved as safe for human consumption by regulators in the Philippines and Bangladesh.

4 Efficacy of Biofortified Crops

The reported biofortified varieties released in different crops through conventional breeding are presented in Table 1.2. The evidence for efficacy of biofortified crops is generated by nutritionists. Biofortified crops are processed, packed, stored and cooked before consumption. Detainment of micronutrient during these processes is

Table 1.2 Status of release of biofortified crop varieties

| Micronutrient | Crop | Variety/hybrid | Status | Country | Reference |
|---------------|--------------|---|---------------------|-----------|---|
| Iron | Rice | IR68144-3B-2-2-3 | Improved line | India | Garg et al. (2018) |
| | | Jalmagna | Traditional variety | India | Gregorio et al. (2000) |
| | Pearl millet | Dhanshakti ICMH 1201 | Released | India | Rai et al. (2013) |
| | | Chakli Hybrids: ICMH 1202, ICMH 1203, ICMH 1301 | Released | India | Govindaraj et al. (2019) |
| | Sorghum | ICSR14001, ICSH 14002 | Released | India | Garg et al. (2018) |
| | | Hybrids: ICSA 661 × ICSR 196 ICSA 318 × ICSR 94 ICSA 336 × IS 3760 | Released | India | |
| | | Parbhani Shakti | Released | India | https://www.icrisat.org/india-gets-its-first-biofortified-sorghum/ |
| | Lentil | 12KNICSV (Deko)-188, 12KNICSV-22 (Zabuwa) | Released | Nigeria | Garg et al. (2018) |
| | | IPL 220 L 4717 | Released | India | Yadava et al. (2018) |
| | Cowpea | Pant Lobia 1, Pant Lobia 2, Pant Lobia 3, Pant Lobia 4 | Released | GBPUA&T | Yadava et al. (2018) |
| | | ICTA Superchiva, ICTA Peten, ICTA Chorti | Released | Guatemala | Andersson et al. (2017) |
| | Bean | CorpoicaRojo 39, CorpoicaRojo 43, Bio 101, Bio 107 | Released | Columbia | Andersson et al. (2017) |

(continued)

Table 1.2 (continued)

| Micronutrient | Crop | Variety/hybrid | Status | Country | Reference | |
|---------------|------|---|-------------|------------------------------|---|----------------------|
| | | MOORE 88002, RWR 2154, RWR 2245, MAC 44 and Nyiramuhondo | Released | Uganda | https://www.icrisat.org/release-of-biofortified-bean-varieties-in-uganda/ | |
| | | COD MLV 059, PVA 1438, Nain de Kyondo, COD MLB 032, Cuarentino, COD MLB 001, HM 21-7, RWR 2245, VCB 81013 | Released | Democratic Republic of Congo | Andersson et al. (2017) | |
| | | BRS Agreste, BRS Pontal, BRS 9435 Cometa | Released | Brazil | Andersson et al. (2017) | |
| | | Fortaleza | Released | Bolivia | Andersson et al. (2017) | |
| | | MIB (NUT) 396-33, MIB (NUT) 397-72 | Released | Honduras | Andersson et al. (2017) | |
| | | INTA Ferroso, INTA Nutritivo | Released | Nicaragua | Andersson et al. (2017) | |
| | | IDIAP NUA 24, IDIAP NUA 27 | Released | Panama | Andersson et al. (2017) | |
| | | MAC 44, RWV 1129, CAB 2, RWR 2245, RWR 2154, RWV 3316, RWV 3006, RWV 3317, MAC 42, RWV 2887 | Released | Rwanda | Andersson et al. (2017) | |
| | | Wheat | WB2 | Released | India | Yadava et al. (2018) |
| | | Maize | HHB 229 | Released | India | Yadava et al. (2018) |
| | | | AHB 1200 | Released | India | Yadava et al. (2018) |
| | | Pomegranate | Solapur Lal | Released | India | Yadava et al. (2018) |

| | | | | | |
|---------|--------|---|----------|-----------------|---|
| | Rice | BRRIdhan62, BRRIdhan64, BBRIdhan72 | Released | Bangladesh | HarvestPlus progress report (2014) https://www.harvestplus.org/sites/default/files/publications/Biofortification_Progress_Briefs_August2014_WEB_2_0.pdf |
| | Lentil | Barimasur-4, Barimasur-5, Barimasur-6, Barimasur-7, Barimasur-8 | Released | ICARDA | HarvestPlus progress report (2014) https://www.harvestplus.org/sites/default/files/publications/Biofortification_Progress_Briefs_August2014_WEB_2_0.pdf |
| | | ILL 7723, Khajurah-1, Shital, Sisir, Sekhar, Simal Alemaya | Released | Nepal | Andersson et al. (2017) |
| | | Idlib-2, Idlib-3 | Released | Ethiopia | Andersson et al. (2017) |
| | Beans | RWR 2245, RWR 2154, MAC 42, MAC 44, CAB 2, RWV 1129, RWV 3006, RWV 3316, RWV 3317, RWV 2887 | Released | Syria Rwanda | Andersson et al. (2017) Andersson et al. (2017) |
| Zinc | Wheat | BHU 1, BHU 2, BHU 3, BHU 5, BHU 6, BHU 17, BHU 18 PBW1Zn | Released | | Yadava et al. (2018) |
| | | NR 419, 42, 421, Zincol | Released | India | Yadava et al. (2018) |
| | Rice | Jalmagna | Released | India | HarvestPlus progress report (2014) Biofortification_Progress_Briefs_August2014_WEB_2_0.pdf |
| | Maize | ICTA HB-18, ICTA B-15 | Released | Mexico | Gregorio et al. (2000) |
| | Maize | BIO-MZN01 | Released | Colombia | Maqbool and Beshir (2019) |
| | Bean | BIO-101, BIO 107 | Released | Colombia | Maqbool and Beshir (2019) |
| Protein | Rice | | Released | NRRI | Beintema et al. (2018) |

(continued)

Table 1.2 (continued)

| Micronutrient | Crop | Variety/hybrid | Status | Country | Reference |
|-----------------------------------|--------------|--|----------------------|----------|---|
| Protein and zinc | Wheat | CR Dhan 310, CR Dhan 311 | | | http://pib.nic.in/PressReleaseframePage.aspx?PRID=1566398 |
| | | PusaTejas (HI 8759) | Released | India | Yadava et al. (2018) |
| Protein, iron, zinc | | Pusa Ujala (HI 1605), MACS 4028 (d) | Released | India | Yadava et al. (2018) |
| Low erucic acid | Mustard | Pusa Mustard 30 | Released | India | Yadava et al. (2018) |
| Low erucic acid and glucosinolate | | Pusa Double Zero Mustard 31 | Released | India | Yadava et al. (2018) |
| β Carotene | Wheat | HI 8627 | Released | India | Garg et al. (2018) |
| | Sweet potato | Bhu Sona | Release | India | Yadava et al. (2018) |
| | Cauliflower | Pusa Beta Kesari 1 | Release | India | Yadava et al. (2018) |
| Anthocyanin | Wheat | NABIMG-9, NABIMG-10, NABIMG-11 | Germplasm registered | NABI | Garg et al. (2018) |
| | | Indigo | Released | Austria | Havrilentova et al. (2014) |
| | | PS Karkulka | Released | Slovakia | Havrilentova et al. (2014) |
| | | Black grained wheat | Released | China | Havrilentova et al. (2014) |
| | Sweet potato | Bhu Krishna | Release | India | Yadava et al. (2018) |
| QPM (lysine and tryptophan) | Maize | CML 176, CML 176 \times CML 186, HQPM-1, HQPM-4, HQPM-5, | Released | Mexico | Garg et al. (2018) |

| | | | |
|---|----------|--------------|-----------------------|
| HQPM-7, VivekQPM-9, FQH-4567 | Released | India | Yadava et al. (2018) |
| Pusa HM4 improved, Pusa HM8 improved, Pusa HM9 improved | Released | India | Hossain et al. (2018) |
| Pusa HM4, Pusa HM 8, Pusa HM 9 | Released | China | Garg et al. (2018) |
| CML 140, CML 194, P70 | Released | Vietnam | Garg et al. (2018) |
| CML 161 × CML 165 | Released | Mexico | Garg et al. (2018) |
| CML 142 × CML 176, CML 142 × CML 150, CML 176 × CML 170, CML 186 × CML 149, CML 176 × CML 186 | Released | | |
| QS-7705 | Released | South Africa | Garg et al. (2018) |
| GH 132-28 | Released | Ghana | Garg et al. (2018) |
| Obatampa | Released | Guinea | Garg et al. (2018) |
| Obatampa | Released | Benin | Garg et al. (2018) |
| Obangaina | Released | Uganda | Garg et al. (2018) |
| Susma | Released | Mozambique | Garg et al. (2018) |
| BR-451, BR-473 | Released | Brazil | Garg et al. (2018) |
| FONIAP | Released | Venezuela | Garg et al. (2018) |
| INIA | Released | Peru | Garg et al. (2018) |
| ICA | Released | Colombia | Garg et al. (2018) |
| HQ-31 | Released | Honduras | Garg et al. (2018) |
| HQ-61 | Released | El Salvador | Garg et al. (2018) |
| HB-Proticta | Released | Guatemala | Garg et al. (2018) |

(continued)

Table 1.2 (continued)

| Micronutrient | Crop | Variety/hybrid | Status | Country | Reference |
|---|--------------|---|----------|-----------|---|
| High provitamin-A, high tryptophan and lysine | | NB-Nutrinta, HQ INTA-993 | Released | Nicaragua | Garg et al. (2018) |
| | | Pusa Vivek QPM improved | Released | India | Yadava et al. (2018) |
| | | 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 | Released | India | Yadava et al. (2018) |
| QPM plus Provitamin A | Maize | Pusa Vivek QPM 9 | Released | India | Yadava et al. (2018) |
| Kunitz trypsin inhibitor | Soybean | NRC 127 | Released | India | Yadava et al. (2018) |
| Vitamin A | Sorghum | UMUCASS 36, UMUCASS 37, UMUCASS 38 | Released | Nigeria | https://www.iita.org/news-item/nigeria-releases-cassava-higher-pro-vitamin-fight-micronutrient-deficiency/ |
| | Maize | A0905-28 and A0905-32 | Released | IITA | Onuegbu et al. (2017) |
| | Sweet potato | Ejumula, Kakamega, Vita, Kabode, NASPOT 7, NASPOT 8, NASPOT 9 O, NASPOT 10 O, NASPOT 12 O, NASPOT 13 O and Dimbuka-Bukulula | Released | Uganda | Mwanga et al. (2007, 2009, 2016) |
| | Cassava | | Released | Nigeria | Andersson et al. (2017) |