Chapter 12
Nutritionally Enhanced Wheat for Food and Nutrition Security

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Abstract The current and future trends in population growth and consumption patterns continue to increase the demand for wheat. Wheat is a major source and an ideal vehicle for delivering increased quantities of zinc (Zn), iron (Fe) and other valuable bioactive compounds to population groups who consume wheat as a staple food. To address nutritious traits in crop improvement, breeding feasibility must be assessed and nutrient targets defined based on their health impact. Novel alleles for grain Zn and Fe in competitive, profitable, Zn enriched wheat varieties have been accomplished using conventional breeding techniques and have been released in South Asia and Latin America, providing between 20% and 40% more Zn than local commercial varieties and benefitting more than four million consumers. Future challenges include accelerating and maintaining parallel rates of genetic gain for productivity and Zn traits and reversing the trend of declining nutrients in wheat that has been exacerbated by climate change. Application of modern empirical and analytical technologies and methods in wheat breeding will help to expedite genetic progress, shorten time-to-market, and achieve mainstreaming objectives. In exploiting synergies from genetic and agronomic options, agronomic biofortification can contribute to achieving higher Zn concentrations, stabilize Zn trait expression, and increase other grain minerals, such as selenium or iodine. Increasing Fe bioavailability in future breeding and research with other nutrients and bioactive compounds is warranted to further increase the nutritious value of wheat. Crop profiles must assure value propositions for all actors across the supply chain and consider processors requirements in product development.

Keywords Nutritional quality · Biofortification · Micronutrients · Zinc · Yield gains · Genomic selection

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M. P. Reynolds, H.-J. Braun (eds.), *Wheat Improvement*,
https://doi.org/10.1007/978-3-030-90673-3_12

12.1 Learning Objectives

- Understanding product development prospects for nutritional quality traits in wheat breeding and the knowledge to develop a roadmap for application.
- Mainstreaming nutritional quality traits in wheat breeding and novel approaches.
- Parental selection, crossing strategies, speed breeding and selection strategies.
- Integration of genomic selection and population improvement approaches for simultaneous gains for grain yield and Zn concentration.
- Product deployment and value chain development for biofortified wheat.

12.2 Introduction

12.2.1 Improving Nutrition of Crops for Human Health

In the past, the agriculture sector focused on producing enough food for a rapidly growing global population, in large part by increasing the production of widely consumed, acceptable, cheap, high calorie staple food crops, including wheat [1]. Yet, food insecurity and malnutrition remain a challenge across the lifespan and may worsen as result of a still rising global population, climate change, and the recent COVID-19 pandemic. Forty-seven million children under five years are too thin for their age, chronic undernutrition affects 144 million children (<5 years), 462 million adults are underweight, and an estimated two billion people are affected by one or more micronutrient deficiencies [2]. Vitamin A, iron, zinc, and iodine deficiencies are the most common worldwide (Table 12.1). Even more alarming are

Table 12.1 Global prevalence rates for key micronutrients and consequences of deficiency

Micronutrient	Consequences of deficiency	Estimated global prevalence rates for key population groups
Vitamin A	Impaired vision; night blindness; increased risk of morbidity and mortality	29% of children (<5 year) and 15% of pregnant women are vitamin A deficient
Iron	Leading cause of anemia; impaired physical and cognitive performance; increased risk of neonatal and maternal mortality	42% of children (<5year) and 29% of women are anemic, with between 30% and 50% of all anemia cases attributed to iron deficiency
Zinc	Stunted growth and development; impaired immune function; loss of appetite; cell damage; increased risk of T2DM and CVD	17% of the global population is at risk of inadequate zinc intake
Iodine	Impaired thyroid function; goiter; abnormal growth and developmental, including irreversible brain damage.	29% of school-aged children (6–12 year) have inadequate iodine intake

With data from [3]

the rates of overweight and obesity and diet related non-communicable diseases (NCDs) that are increasing at a devastating pace, particularly in low- and middle-income countries (LMICs). Nearly two billion adults and 38 million children (<5 years) are overweight or obese and NCDs are the cause of more than 70% of global deaths every year [2]. The number of overweight and obese people is expected to increase by an additional 40% by 2025, if the rate of increase remains unchanged [2].

In recent years there has been a shift in resources and political will that has encouraged researchers across a range of disciplines, including agriculture, public health and nutrition, to address not only the quantity of staple food crops but also the quality (i.e., potential nutritional impact) [1]. One of the biggest advancements was the nutritional enrichment of crops called "biofortification", using agriculture as vehicle for a public health intervention. Biofortification is the use of conventional plant breeding, bioengineering techniques, and agronomic practices to improve the nutritional value of staple food crops [4]

Wheat is an ideal crop for biofortification and conventionally bred high zinc (Zn) wheat is one of its success stories. Wheat ranks second in global cereal production and is a valuable source of nutrients and other non-nutritious bioactive compounds (see Chap. 24). For example, compared to other staple cereal grains, such as maize and rice, wheat is relatively high in protein content (average protein content in wheat cultivars is between 10% and 15% per dry weight) and it supplies an average of 20% of daily global protein intake for humans [5]. However, while wheat has a wealth of genetic resources available in its secondary and tertiary gene pools [6], the levels of micronutrients, such as Zn, in commonly consumed, commercial varieties are not high enough to meet daily requirements of people in countries where wheat constitutes the main source of calories. Thus, biofortified whole grain wheat can supply essential micronutrients to vulnerable at-risk populations with inadequate intake, particularly young children and women of reproductive age [4].

12.2.2 Importance of a Whole Grain Diet

For optimal nutrition and health, global dietary guidelines recommend consumption of whole wheat grain [7]. Whole grain wheat includes the bran, germ and endosperm, whereas in refined grain, only the endosperm remains after milling [8]. Nutritionally superior, whole grain wheat provides energy, protein, some fats, vitamins, minerals, dietary fiber, and bioactive compounds [8]. If the bran and germ are removed during processing, the refined flour provides mostly energy in the form of carbohydrates (~80%), and very little other nutrients, dietary fiber, or bioactive compounds.

Dietary fiber and bioactive components provide important health benefits to humans. Dietary fiber is vital for maintaining gut health through its fermentation in the large intestine, which produces short chain fatty acids (SCFA) and increases the abundance of beneficial gut bacteria [9]. Higher intakes of whole grains and dietary fiber are causally associated with overall better health, including a lower risk of metabolic syndrome, reductions in overweight and obesity, and reduced risk of mortality and in the incidence of a wide range of diet related NCDs (9).

Bioactive compounds are heterogeneous group of molecules found in small quantities in wheat, and include tocopherols, carotenoids, certain minerals, and phenolic compounds [10] (Table 12.2). While most of these compounds do not provide any nutritional value, they have strong antioxidant properties and provide protection against inflammation and oxidative stress [11]. Although the mechanisms of action are not fully understood, in vitro, animal, and epidemiological studies suggest that consumption of bioactive compounds may help to reduce risk factors and the incidence of cardiovascular disease (CVD), type 2 diabetes mellitus (T2DM), certain cancers, and age-related eye disease [10–15].

12.2.3 Significance of Processing, Retention and Bioavailability on Nutritional Impact of Wheat

A number of factors affect the nutrition and health impact of biofortified wheat. Nutrients and non-nutritious bioactive compounds are not distributed equally throughout the edible portion of the plant and the concentration of these compounds in the grain is under genetic control and affected by growing conditions. Most of the B-vitamins and carotenoids are found in the germ fraction; more than 80% of tocopherol is found in the pericarp, testa, and aleurone; and most of the minerals and phenolic compounds have been reported in the aleurone and bran layers [8, 16] (Fig. 12.1). Hence, it is important to consider the extent and type of milling when determining the potential health benefits of biofortified wheat.

A study of the retention of Zn in biofortified and non-biofortified conventional wheat varieties in different grain milling fractions and flours of various extraction rates showed that biofortified and conventional wheat flour milled at a very low 60% extraction level contained only 14% of the Zn concentration compared to whole grain wheat [17]. In contrast, when milled at 80% extraction, the biofortified wheat flour contained 13 ppm more Zn than the non-biofortified variety [17]. Furthermore, two absorption studies with foods made from biofortified and non-biofortified wheat flour showed that Zn absorption was significantly increased with biofortification (by up to 40%), regardless of the extraction level [18, 19], thereby helping to meet dietary Zn requirements without changing food sources.

Additionally, not all compounds that are present in the plant can be absorbed; for most compounds to produce a physiological effect, they need to be bioavailable (i.e., absorbed in sufficient quantity and transported into the bloodstream). Absorption of nutrients and non-nutritious bioactive compounds are affected by the food matrix; the amount and form of the compound; dietary promoters (e.g., dietary fat and protein) and inhibitors (e.g., phytic acid); and processing conditions [8].

Table 12.2 Potential health benefits of nutritious and non-nutritious bioactive compounds in whole grain wheat

Bioactive compounds	Example(s)	Known/purported health benefits
B-vitamins	Thiamine (B1), riboflavin (B2), niacin (B3), pyridoxine (B6), folate (B9)	Essential group of water-soluble vitamins required for energy production, one carbon metabolism, DNA synthesis/repair, red blood cell production. Antioxidant properties; associated with decreased risk of cataracts; migraine prevention; intakes associated with improved risk factors for T2DM (e.g., increase intestinal absorption of sugar and reduced risk of hyperglycemia) and stroke (e.g., may lower blood pressure and help prevent dyslipidemia and atherosclerosis); may have anti-carcinogenic activity
Vitamin E	Tocopherols, tocotrienols	Essential vitamin found in food as eight fat-soluble isomers; antioxidant properties; anti-inflammatory agent; intake associated with lower risk of cancer, CVD, T2DM and obesity (e.g., lowers blood cholesterol levels and improves insulin sensitivity)
Minerals	Zinc, iron, selenium, magnesium, manganese	Essential micronutrients required for proper immune function and physical growth; antioxidant properties; role in prevention of age-related eye diseases; role in prevention of chronic diseases, including T2DM, CVD and cancer (e.g., zinc may improve glycemic control in diabetic patients, higher magnesium intake is associated with lower risk of hypertension and metabolic syndrome, selenium intake is associate with lower risk of cancer and cancer-related mortality)
Choline and compounds	Choline, betaine	Essential nutrient and methyl donor; required for very low-density lipoprotein assemble and secretion; neuroprotective effect (i.e., essential for normal fetal brain growth and development); intake associated with lower risk of fatty liver disease, optic neuropathies (e.g., glaucoma), neural tube disorders, preeclampsia, and inflammation in asthma patients
Phenolic acids	Ferulic acid	Intake associated with reduced risk of T2DM (e.g., may help improve insulin sensitivity) and certain cancers (e.g., colon, prostate, and breast cancer) by improving insulin sensitivity
Phenolic lipids	Alkylresorcinols	Plays a role in blood clotting and may help reduce risk factors for obesity and CVD (e.g., inhibiting triglyceride synthesis)
Lignans (phytoestrogens)	Secoisolariciresinol diglycoside	May play a role in preventing CVD and breast cancer

(continued)

Table 12.2 (continued)

Bioactive compounds	Example(s)	Known/purported health benefits
Phytosterols	Sisterol	Intake is associated with reduced risk factors for CVD and T2DM (e.g., may help lower blood cholesterol levels and circulating cholesterol, blood lipids, blood pressure, and blood sugars)
Non-provitamin A carotenoids	Lutein, zeaxanthin	May reduce risk of macular degeneration and cataracts
Phytic acid	myoinositol hexaphosphate	Intake associated with protection against kidney stones and reduced risk of some cancers; may help lower blood lipids

Sources: [10–15]

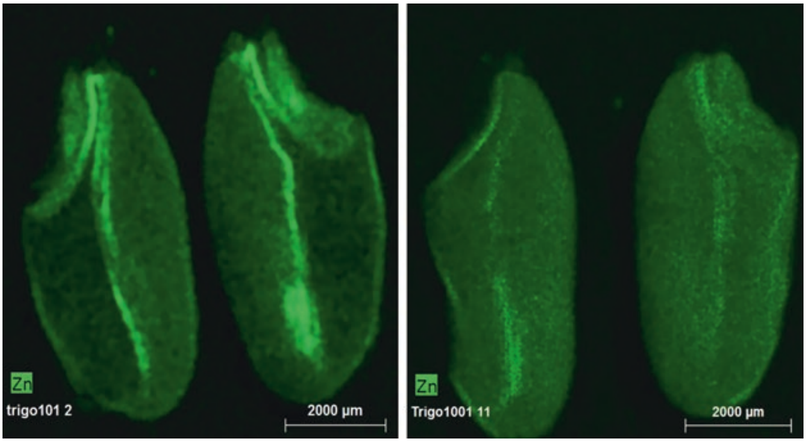

Fig. 12.1 Localization of zinc in wheat grain with µXRF (left high zinc wheat' Zinc-shakti', right CIMMYT control variety 'Baj')

12.3 Crop Improvement for Nutritional Quality

12.3.1 Setting Breeding Target Levels

Target levels were set to achieve a measurable impact on health for the primary target population: women of reproductive age and children [4]. For wheat, a target increment of +12 ppm for Zn need to be added to country or region-specific baselines to achieve a required contribution to the Estimated Average Requirement for Zn from the biofortified wheat (Fig. 12.2). While a global baseline can be assumed at 25 ppm and are derived from commercial varieties, country specific baselines may vary widely. Target increments are adjusted for per capita intake, bioavailability, and retention losses during processing, storage and cooking [20]. Hence, target increments can be achieved by breeding for higher micronutrient concentration and

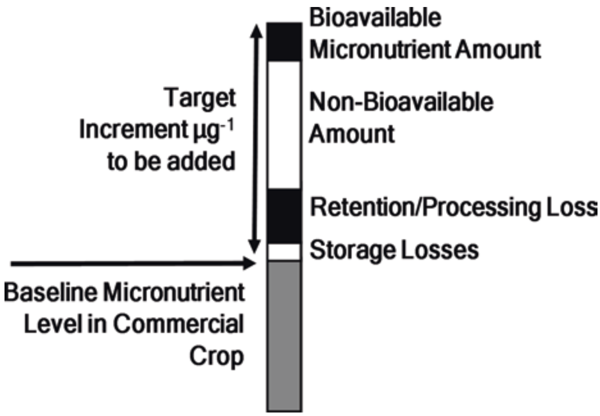

Fig. 12.2 Setting breeding target levels for grain Zn in wheat

by increasing the bioavailability and retention of micronutrients in the final product. In addition, it is projected that climate change will drastically affect the mineral and protein content in wheat. Gradual increases to target levels may be required, but our understanding is limited. Thus, there is an urgent need to quantify the impact of climate change on the nutritional quality of wheat.

12.3.2 Genetic Diversity for Nutritional Quality Traits

Large-scale screening of the genetic diversity spectrum in gene banks and collections at the International Maize and Wheat Improvement Center (CIMMYT) and partner institutions revealed genetic variation for minerals in primitive wheats, wild relatives, and landraces that would surpass targets, but insufficient variation in commercial varieties and breeding program materials. However, achieving Zn varieties with 40 ppm or higher Zn requires using unadapted genetic resources and pre-breeding materials. Though there is a large variation for Zn and Fe in wheat progenitor species, care must be taken in analysis as grain shriveling, which can be also caused be abiotic or biotic stress, may lead to a concentration effect. Grain nutrient content rather than concentration should be determined [4]. Contaminant Fe and Zn from soil/dust or threshing equipment can be assessed by measuring index elements such as Al, which are abundant in nature but absent in plants, or by measuring Ti and Cr to estimate contamination from metal parts. Breeding programs require fast, accurate, and inexpensive methods for screening large numbers of breeding lines and germplasm for nutritional traits. Energy dispersive X-ray fluorescence (EDXRF) has been investigated as a reliable alternative to ICP-based methods for high-throughput analysis of Zn and Fe in wheat.

Wheat grown in Central and East Asia reports grain Zn concentrations ranging from 14 to 35 ppm in 150 bread wheat lines grown in China, to 20–39 ppm in 66 advanced wheat genotypes grown in Kazakhstan, Kyrgyzstan and Tajikistan. Grain Zn concentration is even more variable among wheat grown in South Asia and Mexico: 29–40 ppm of grain Zn has been reported among 40 CIMMYT bread wheat lines [21]; 30–98 ppm among 518 accessions of *T. dicoccoides*; 27–53 ppm among 93 advanced lines developed by the crossing of Mexican landraces, *Triticum dicoccoides* and *Ae. Tauschii,* with durum and common wheat genotypes [22]; and 25–60 ppm in 185 recombinant inbred lines derived from crossing *T. spelta* and *T. aestivum* grown under field conditions. Grain Fe concentration usually varies by 1.2-fold in tetraploid cultivars, 1.8-fold in hexaploids cultivars, and 2.9-fold in diploid cultivars. Additionally, a set of Indian and Turkish landraces showed large variation in macrominerals[1] (1.7–6.4 fold), certain microminerals[2] (3.6–5.6 fold) and protein (2.2 fold) [23].

12.3.3 Targeted Breeding Approach

The HarvestPlus crop development alliance with CIMMYT and other national public and private sector partners and centers of excellence focused on improving grain Zn and Fe concentrations in South Asia, where Zn and Fe deficiency are widespread [2]. To date, Zn concentrations between 50% and 100% of the target increment have been achieved in competitive first and second wave varieties in India, Pakistan, Bangladesh and Nepal [24]. In developing these varieties, Zn density from synthetic wheat lines derived from wild wheat relatives, *Aegilops tauschii* (D genome donor of wheat), *Triticum spelta* and wild *T. dicoccon* were combined with yield and farmer preferred trait packages using elite breeding lines and major local varieties in crosses. In addition, due to the positive correlation between Zn and Fe content, Fe increased by approximately 0.5 ppm annually via correlated selection response. A similar increase was observed for other micronutrients positively associated with Zn, such as Mn and Mg [24].

In targeted breeding, each year 400–500 simple crosses are made between elite high/moderate Zn lines, elite high Zn lines, and best lines with normal Zn. Segregating populations from these crosses are advanced and selected for agronomic and disease resistance. F5/F6 lines retained are selected for grain characteristics and grain Zn and Fe concentration. High Zn F5/F6 lines are advanced to stage 1 replicated yield trials in Zn-homogenized fields at CIMMYT, Mexico, which show good grain Zn prediction in South Asia and other target population of environments (TPEs). Grain Zn and Fe is determined for lines with equal or higher

[1] Macrominerals: calcium (Ca), potassium (K), Magnesium (Mg), sodium (Na), phosphorus (P), and sulphur (S).

[2] Microminerals: Zinc (Zn), Iron (Fe), Copper (Cu), Manganese (Mn).

yields compared to checks following analyses for end-use processing quality. Varieties for South Asia must have resistance to Ug99 and yellow rust and lines are also simultaneously phenotyped for resistance during two seasons at Njoro, Kenya. The selected superior lines are then distributed to national agricultural research system (NARS) partners in South Asia and other TPEs in international nurseries which serve as germplasm distribution and investigative tools [21].

12.3.4 Genetic Architecture and Association of Nutritional Quality Traits in Wheat

Zn concentration on a global scale varies widely due to a variation of variable and permanent environmental factors, in particular edaphic conditions as soil Zn deficiency is widespread. Ranges of 20–31 ppm in grain Zn have been found [25] and genotypes showed consistent ranking across sites and years for grain Zn concentrations [26, 27].

There is a positive significant relationship with Zn concentration and N, Ca, Cu, Fe, K, Mg, Mn, Mo, P, S and Se concentrations in wheat grain (Cu et al. 2020). Grain Zn concentration is more strongly correlated with grain Cu, Fe, Mn, P and S ($r = 0.61$, 0.46, 0.43, 0.53, 0.46, respectively) than with Ca, K, Mg, Mo and Sr ($r = 0.36$, 0.20, 0.33, 0.18, 0.15, respectively) [26]. Given the positive correlation of grain Zn with these elements, increases in grain Zn concentration may also help to increase the grain Ca, Cu, Fe, K, Mg, Mn, Mo, P, and S concentrations. Co-localization of grain Zn and Fe QTLs on chromosome 2B has been reported [30]. Similarly, a slight increase in S concentration reportedly increased the grain Zn concentration, possibly due to the increase in the amino acid methionine that further increased levels of phytosiderophores and nicotinamide, which are involved in uptake and translocation of Zn (Fig. 12.3).

With respect to the relationship between grain Zn concentration and grain yield, the evidence is conflicting. The most recent data suggest there is no direct trade-off between increased grain Zn concentration and yield in wheat once Zn density is established in high yielding elite donors, which is in contrast to previous studies. These reported differences may be due to linkage drag in early biofortification materials from using unadapted high Zn parents, as a negative correlation of grain Zn and grain yield was observed in unadopted wild sources. Identifying the genomic regions that regulate the accumulation of Zn and Fe in grain without any confounding effects on yield or pleiotropic Zn and Fe QTL with seed size or other yield components would allow breeders to develop high yielding biofortified cultivars.

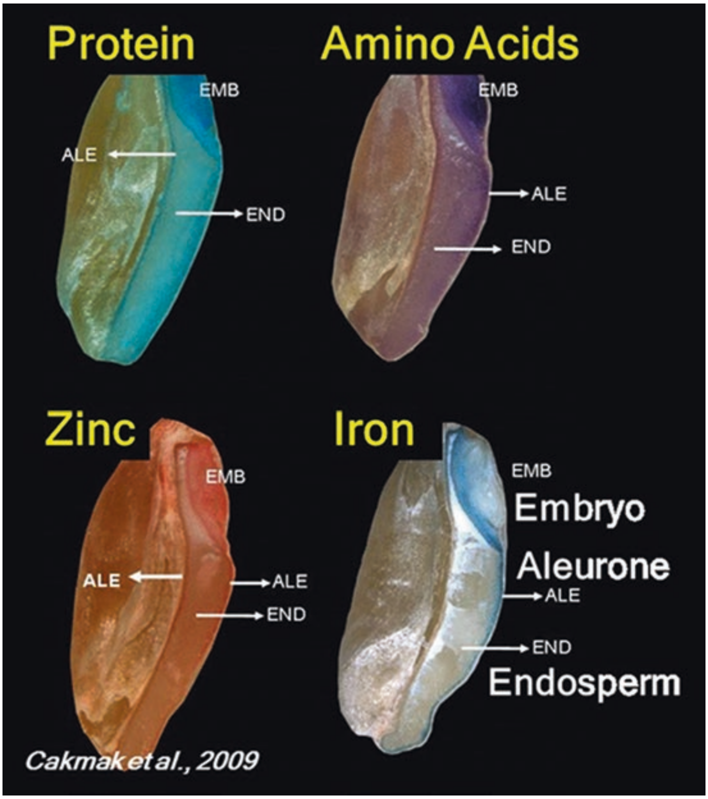

Fig. 12.3 Co-localization of grain Zn and Fe with protein and amino acids

12.3.5 Genetic Control of Nutritional Quality Traits

An enabling knowledge base regarding the genetic control of nutritional traits is crucial for breeding effectiveness. Genetic and QTL mapping studies at CIMMYT revealed that small-to-intermediate-effect QTL of additive effects govern the inheritance of grain Zn and Fe. Several studies also identified promising large-effect QTL regions for increased grain Zn on chromosomes 1B, 2B, 3A, 4B, 5B, 6B and 7B and some QTL regions have a pleiotropic effect for grain Fe (Hao et al. 2014; Velu et al. 2016; Cu et al. 2020). Moreover, 2B and 4B QTL has a pleiotropic effect for increased thousand-kernel weight (TKW), suggesting that a simultaneous improvement of grain Zn and consumer preferred seed size is possible. Four QTLs have been identified for combination in adequate genetic backgrounds in forward breeding (Hao et al. 2014).

Although several QTL of moderate effect on grain Zn have been found in different germplasm sources, the genetic control of the trait appears polygenic. Multiple years of phenotyping results and several studies at CIMMYT show a relationship

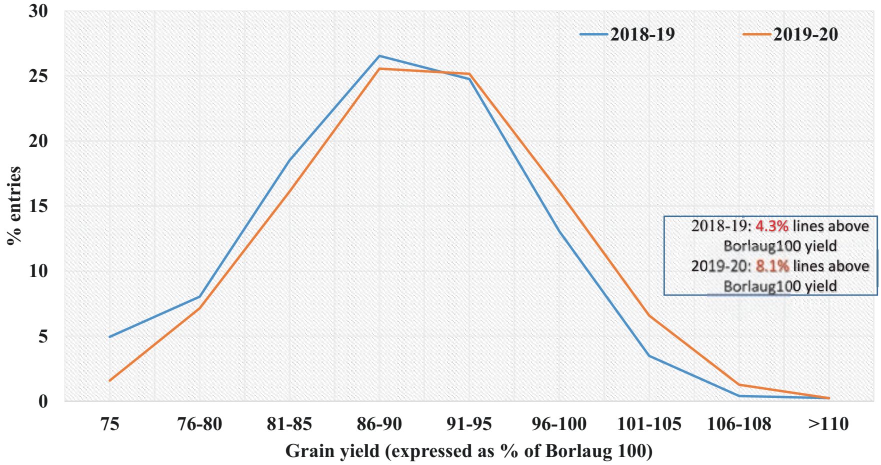

Fig. 12.4 Grain yield trends of wheat lines derived from two cohorts of Zn breeding pipeline evaluated in stage 1 replicated (3 reps) yield trials at Ciudad Obregón 2018–2019 and 2019–2020

between the two traits, while a moderately high heritability for Zn and Fe suggest that grain yield and grain Zn are independently inherited. The variance components from CIMMYT's Ciudad Obregón site in Mexico showed genotypic (main) effects attributed to a larger share of total variation for grain Zn (61%) than the environment (39%), whereas multi-site analyses of an association genetics panel across locations in India showed 27% variation attributed to genotypic effects, 30% variation explained by the genotype-by-environment (GxE) interaction, and 43% by environment and error variance [27].

Recent yield data from the stage 1 yield trials in Ciudad Obregón showed about 1% average yield gain per year was achieved over the past two years while enhancing grain Zn concentration by +1–2 ppm annually (Figs. 12.4 and 12.5), suggesting the feasibility of combining high yield with high Zn concentration. Moreover, the lack of association between grain yield and grain Zn will support their simultaneous genetic gain as realized in CIMMYT's current breeding scheme [24].

12.3.6 Agronomic Biofortification

By exploiting synergies from genetic and agronomic options, agronomic biofortification can help achieve higher Zn concentrations, stabilize Zn trait expression caused by spatial, temporal, and systems environmental fluctuations, and increase other grain minerals, such as selenium or iodine, to nutritionally important levels (see Chap. 24). Zinc has moderate phloem mobility, hence foliar application or a combination of soil and foliar application, markedly increases grain Zn content. Furthermore, grain Zn concentration is severely affected by the availability of a

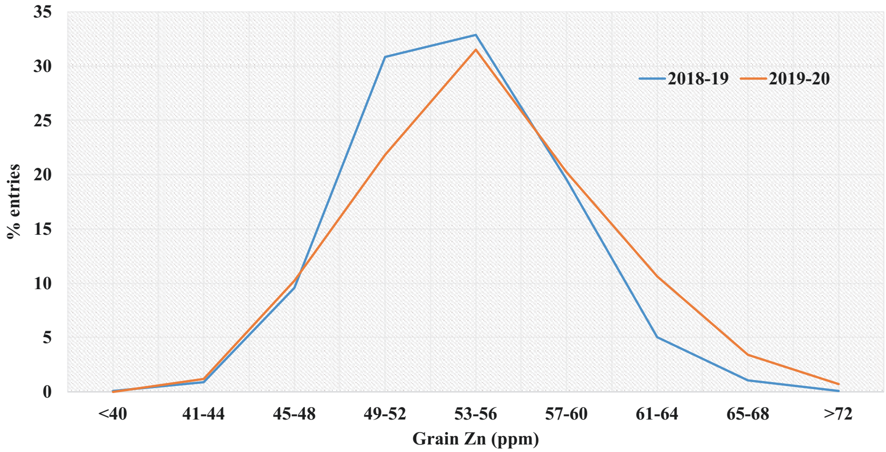

Fig. 12.5 Grain Zn concentration of wheat lines derived from two cohorts of Zn breeding pipeline evaluated in stage 1 replicated (3 reps) yield trials at Ciudad Obregón during 2018–2019 and 2019–2020

physiological pool of Zn in vegetative tissues, hence foliar application substantially increases Zn in the wheat endosperm. Soil Zn application is less effective in increasing grain Zn concentration because of poor Zn mobility and its rapid adsorption in alkaline calcareous soils. Field trial data from India and Pakistan revealed that improved stand establishment for biofortified wheat increased biomass and yield; the better ground cover can reduce evapo-transpirative moisture losses especially under rainfed production.

12.3.7 Mainstreaming Nutritional Quality Traits in Wheat Breeding and Novel Approaches

Maintaining traits of genetic gains for grain yield along with increased grain Zn concentration, thereby closing the yield gap between non-biofortified and biofortified lines (currently 4–6%), poses a major future challenge. For adoption by farmers, the performance of Zn enhanced lines/varieties must be at least on par with current non-biofortified varieties, in the absence of price premiums for Zn wheat. Adding Zn as a core trait in breeding and converting progenitors requires accelerating the breeding cycle, expanding operational scale, phenotyping bread wheat breeding lines for Zn, and then applying the latest technologies in phenotyping, genotyping, molecular-assisted and genomic selection (GS) methods (see Chap. 7). To maximize reach, mainstreaming must be expanded to public and private national program partners and the enabling infrastructure built. This includes optimizing selection environments for Zn to overcome the heterogeneity problem by using soil Zn application in key TPEs.

Capturing favorable and simultaneous additive effects in yield and Zn improvement requires selection indices with weights for yield and Zn, as well as considering heritability and genetic variance estimates in target locations to guide the development of inter-population recurrent selection schemes for crossing well-defined parental lines. Correlated selection response will lead increases in Fe and other positively correlated elements. While the medium high heritability for Zn increases gains in selection, both yield and Zn content are polygenic traits, and an increased breeding effort and new approaches are required to increase allele frequencies and capitalize on transgressive segregation. In order to achieve faster genetic gains, CIMMYT is generating genotypic data for high Zn wheat lines and training populations specific for biofortification breeding established. Prediction models developed using novel statistical genetic models (e.g., gBLUP -Genomic best linear unbiased prediction-), which incorporate available genomic and phenomic information, are validated and utilized in the rapid breeding pipeline to select potential parents and progenies with high breeding values for Zn and grain yield. So far, genomic predictions for Zn and Fe are moderately high (r = 0.4–0.6) across locations in Mexico and India using the association mapping panel from the biofortification program [32]. Therefore, GS models for these traits could also be used to select parents.

12.3.8 Speed Breeding

Modern breeding techniques that use cutting-edge genomics and accelerated breeding cycles are to be exploited to accelerate achieving linear progress, at 1–2% genetic gains per cycle for grain Zn and yield (see Chap. 30). Generally, genetic gain is determined by Eq. 12.1.

Breeder's equation:

$$\Delta g = \frac{\mathrm{i} * \mathrm{r} * \sigma g}{L} \tag{12.1}$$

where:

Δg = Genetic gain
i = selection intensity
r = selection accuracy
σg = genetic variance
L = breeding cycle length

Targeted genetic gain can be achieved at a faster rate by shortening the breeding cycle or generation time rather than selection intensity and heritability, which are highly trait and environment dependent. Shortening the breeding cycle or generation time can be achieved by adopting speed breeding [34]. This is different from shuttle breeding, which was pioneered by N.E. Borlaug in the late 1940s. Shuttle breeding was developed to advance two generations per year and half development

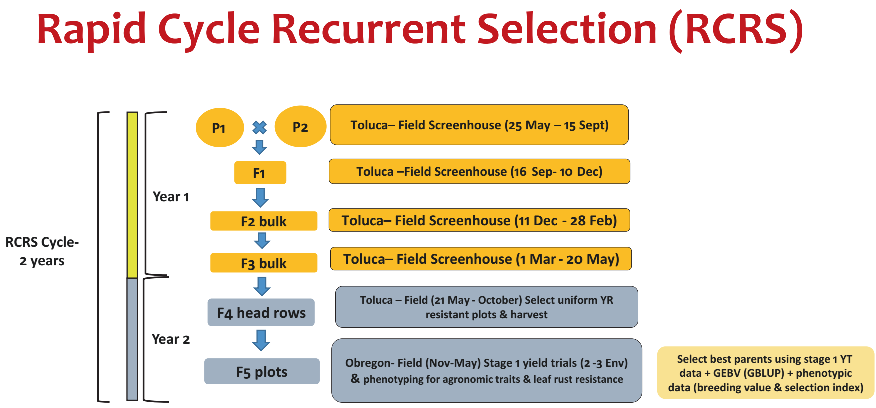

Fig. 12.6 Proposed RCRS breeding scheme with a two-year breeding cycle

Fig. 12.7 Happy wheat plants in a speed breeding facility at CIMMYT, Toluca, Mexico

time, as well as add yield stability, adaptation range, and photoperiod insensitivity by selecting in contrasting environments. Speed breeding allows three to four generations per year, for example, at CIMMYT's Toluca facility.

Further, speed breeding allows faster recombination of elite lines through genomic estimated breeding values. CIMMYT uses a rapid-cycle recurrent selection (RCRS) population improvement approach with a two-year breeding cycle (Fig. 12.6); wheat plants are advanced in greenhouses using a speed breeding green house facility (Fig. 12.7).

12.3.9 Population Improvement

Population improvement increases the allele frequency of positive alleles for grain yield and grain Zn using recurrent selection. In a closed population development system, each cohort (cycle) of materials should originate from crosses between parents from previously evaluated and selected materials.

12.3.10 Genomic Selection

The application of GS in wheat breeding is enabled by the availability of high-throughput molecular markers, which cover the entire genome and facilitate trait value prediction. Experimental studies based on multi-environment wheat trials demonstrated that genomic selection models accurately predict genetic values of complex traits, such as grain yield, grain nutritional quality, or stress adaptation under different conditions [35]. However, prediction accuracy values for grain yield varies widely across different cohorts of materials and at different TPEs and studies that consider GxE interactions are still under development. Nevertheless, retrospective GS analysis showed promising results, supporting its application in breeding.

12.4 Product Development and Dissemination

The aim of the breeding scheme is to extract products from the population improvement scheme to deliver improved wheat lines to NARS partners. CIMMYT focuses on population improvement, introducing new alleles through trait/diversity introgression onto elite parents containing positive alleles that are either absent, or present only in low frequencies in the core germplasm, in forward-breeding/population improvement activities. Introgressing new germplasm needs to be based on yield and Zn values and on a robust selection index.

12.4.1 Adoption and Commercialization of Biofortified Wheat

Traditional breeding focuses on improving traits of known economic value and developing product profiles for existing markets. Traits are targeted for selection based on whether they can provide better crop and/or utilization options to farmers. In general, these traits are related to productivity, biotic/abiotic stress, and end-use quality. Biofortification additionally enhances traits whose value is measured in health and nutrition outcomes. Improvements in nutrition and health status from consuming biofortified wheat occur gradually. Enhanced traits, such as Zn or Fe, are invisible and do not affect sensory characteristics; therefore, crop profiles must assure value propositions for all actors across the value chain and consider processors requirements in product development (see Chap. 11) (Fig. 12.8).

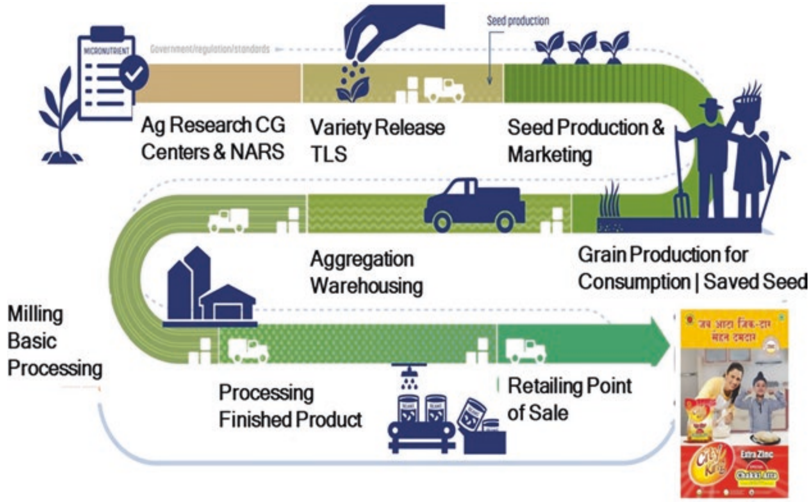

Fig. 12.8 Value chain for biofortified wheat

Producer and consumer insight research is critical for farmer adoption and consumer acceptance. Research and concept testing in India revealed that more than 90% of farmers and rural and urban consumers would definitely or likely grow and consume Zn wheat, once they aware of the health benefits. Overall, awareness of the health benefits from consuming biofortified wheat, in particular minerals, is low and awareness campaigns, demand creation, and promotion materials are important in developing sustainable markets for nutritionally enhanced biofortified crops. Supply chain development is of equal importance, particularly in countries that lack segregation. Identity preservation, quality control, and traceability must be guaranteed when developing procurement systems for timely volume supply for private and institutional buyers. In this context, standards at the grain level were identified as a missing enabler of the wheat value chain making it difficult for buyers to specifically procure high Zn grain. HarvestPlus partnered with the British Standards Institute to create an international Publicly Available Standard (PAS) for Zn with planned publication and use in June 2021; development of a PAS for Fe has also commenced. The PAS are harmonized with breeding targets of the HarvestPlus/CIMMYT crop development alliance and helps facilitate including micronutrients as value added traits and considered in release.

The impact pathway for commercializing biofortified wheat is outlined in Fig. 12.9. The primary beneficiaries of biofortification are smallholder farm households in LMICs who rely on staple crops for caloric and nutrient intakes and often lack reliable access to diversified diets, fortified foods or supplements. In addition, partnerships along the value chain are crucial to catalyzing nutritious, biofortified food systems worldwide that deliver adequate micronutrients through regular diets. To achieve a global reach, it is critical to market and advocate for biofortification at all levels, including developing a regulatory framework for biofortified crops,

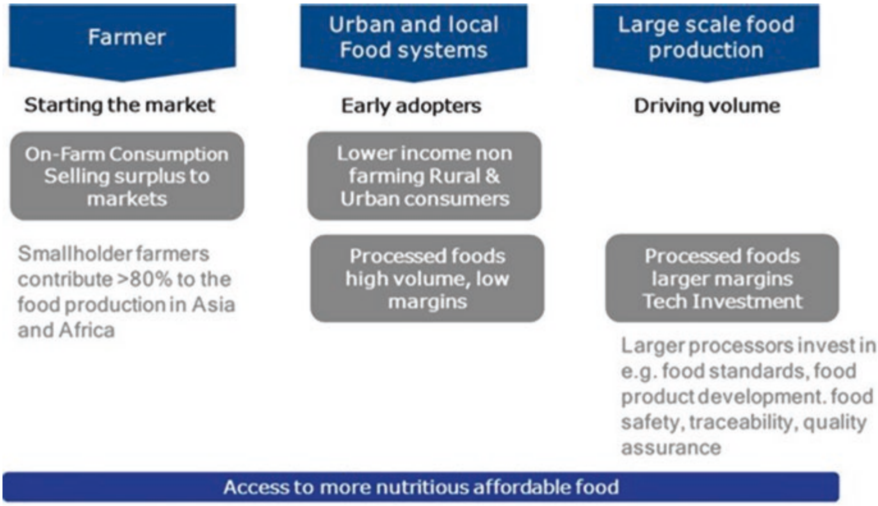

Fig. 12.9 Impact pathway for commercializing biofortified wheat

mainstreaming micronutrients in crop development and in food systems, and incorporating biofortification into public and private policies, programs, and investments.

12.5 Key Concepts

The chapter provides the prospects of wheat improvement for nutritional quality traits, guiding through steps in practical application. Specifically, on the mainstreaming of grain zinc in CIMMYT wheat germplasm using novel approaches of applying modern genomics and quantitative genetics strategies of population improvement coupled with rapid recycling of parents based on true breeding value (TBV) to accelerate rate of genetic gain for grain yield and grain zinc concentration. In addition, product deployment and value chain development for biofortified wheat also discussed.

12.6 Conclusions and Future Perspectives

Crop improvement for nutritional quality is essential to improving public health in developing and developed market economies. Biofortified wheat varieties that provide between 20% and 40% more Zn than local commercial varieties have been released since 2016 in South Asia and are grown by roughly one million households, benefitting more than four million consumers. Through mainstreaming grain Zn, CIMMYT's wheat breeding program will achieve more than 75–80% of elite lines with enhanced Zn (and Fe) within the next ten years. This will be realized using modern genomics and speed breeding techniques to reduce breeding cycle time and accelerate rates of genetic gains for both high yield and increased grain Zn concentration. Eventually, higher frequency of elite wheat lines with high yield, high Zn, and other agronomic traits will become available to NARS partners who can then select and promote biofortified wheat varieties to farmers and consumers in target countries, thus helping to improve global nutrition and food security. Research with other nutrients and bioactive compounds is warranted to further increase the nutritious value of wheat. In exploiting synergies from genetic and agronomic options, agronomic biofortification can contribute to achieving higher mineral concentrations and stabilize Zn trait expression caused by spatial, temporal, and systems environmental fluctuations. Since Zn or Fe content is a quantitatively inherited invisible trait, crop profiles must assure value propositions for all actors across the supply chain and consider processors requirements in product development.

References

1. Poole N, Donovan J, Erenstein O (2020) Agri-nutrition research: revisiting the contribution of maize and wheat to human nutrition and health. Food Policy. https://doi.org/10.1016/j.foodpol.2020.101976
2. FAO, IFAD, UNICEF, WFP, WHO (2020) The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. Rome
3. World Health Organization (2020) Micronutrient database. In: The vitamin and mineral nutrition information system. https://www.who.int/vmnis/database/en/
4. Pfeiffer WH, McClafferty B (2007) HarvestPlus: breeding crops for better nutrition. Crop Sci 7:S88–S105. https://doi.org/10.2135/cropsci2007.09.0020IPBS
5. Shiferaw B, Smale M, Braun HJ, Duveiller E, Reynolds M, Muricho G (2013) Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. Food Secur 5:291–317. https://doi.org/10.1007/s12571-013-0263-y
6. Velu G, Ortiz-Monasterio I, Cakmak I, Hao Y, Singh RP (2014) Biofortification strategies to increase grain zinc and iron concentrations in wheat. J Cereal Sci 59:365–372
7. Reynolds A, Mann J, Cummings J, Winter N, Mete E, Te Morenga L (2019) Carbohydrate quality and human health: a series of systematic reviews and meta-analyses. Lancet 393:434–445. https://doi.org/10.1016/S0140-6736(18)31809-9
8. Luthria DL, Lu Y, John KMM (2015) Bioactive phytochemicals in wheat: Extraction, analysis, processing, and functional properties. J Funct Foods 18:910–925. https://doi.org/10.1016/j.jff.2015.01.001
9. Barber TM, Kabisch S, Pfeiffer AFH, Weickert MO (2020) The health benefits of dietary fibre. Nutrients 12:1–17
10. Gani A, Wani SM, Masoodi FA, Hameed G (2012) Whole-grain cereal bioactive compounds and their health benefits: a review. J Food Process Technol 03. https://doi.org/10.4172/2157-7110.1000146
11. Saini P, Kumar N, Kumar S, Mwaurah PW, Panghal A, Attkan AK, Singh VK, Garg MK, Singh V (2020) Bioactive compounds, nutritional benefits and food applications of colored wheat: a comprehensive review. Crit Rev Food Sci Nutr 61:3197–3210
12. Bruins MJ, Van Dael P, Eggersdorfer M (2019) The role of nutrients in reducing the risk for noncommunicable diseases during aging. Nutrients 11. https://doi.org/10.3390/nu11010085

13. Bjørklund G, Dadar M, Pivina L, Doşa MD, Semenova Y, Aaseth J (2019) The role of zinc and copper in insulin resistance and diabetes mellitus. Curr Med Chem 27:6643–6657. https://doi.org/10.2174/0929867326666190902122155
14. Al-Ishaq RK, Overy AJ, Büsselberg D (2020) Phytochemicals and gastrointestinal cancer: cellular mechanisms and effects to change cancer progression. Biomolecules 10. https://doi.org/10.3390/biom10010105
15. Abdel-Aal ESM, Akhtar H, Zaheer K, Ali R (2013) Dietary sources of lutein and zeaxanthin carotenoids and their role in eye health. Nutrients 5:1169–1185. https://doi.org/10.3390/nu5041169
16. Li J, Liu J, Wen W, Zhang P, Wan Y, Xia X, Zhang Y, He Z (2018) Genome-wide association mapping of vitamins B1 and B2 in common wheat. Crop J 6:263–270. https://doi.org/10.1016/j.cj.2017.08.002
17. Hussain S, Maqsood MA, Rengel Z, Aziz T, Abid M (2013) Estimated zinc bioavailability in milling fractions of biofortified wheat grains and in flours of different extraction rates. Int J Agric Biol 15:921–926
18. Rosado JL, Hambidge KM, Miller LV, Garcia OP, Westcott J, Gonzalez K, Conde J, Hotz C, Pfeiffer W, Ortiz-Monasterio I, Krebs NF (2009) The quantity of zinc absorbed from wheat in adult women is enhanced by biofortification. J Nutr 139:1920–1925. https://doi.org/10.3945/jn.109.107755
19. Signorell C, Zimmermann MB, Cakmak I, Wegmüller R, Zeder C, Hurrell R, Aciksoz SB, Boy E, Tay F, Frossard E, Moretti D (2019) Zinc absorption from agronomically biofortified wheat is similar to post-harvest fortified wheat and is a substantial source of bioavailable zinc in humans. J Nutr 149:840–846. https://doi.org/10.1093/jn/nxy328
20. Van Der Straeten D, Bhullar NK, De Steur H, Gruissem W, MacKenzie D, Pfeiffer W, Qaim M, Slamet-Loedin I, Strobbe S, Tohme J, Trijatmiko KR, Vanderschuren H, Van Montagu M, Zhang C, Bouis H (2020) Multiplying the efficiency and impact of biofortification through metabolic engineering. Nat Commun 11:1–10. https://doi.org/10.1038/s41467-020-19020-4
21. Velu G, Singh RP, Huerta-Espino J, Peña RJ, Arun B, Mahendru-Singh A, Mujahid MY, Sohu VS, Mavi GS, Crossa J, Alvarado G, Joshi AK, Pfeiffer WH (2012) Performance of biofortified spring wheat genotypes in target environments for grain zinc and iron concentrations. Field Crop Res 137:261–267. https://doi.org/10.1016/j.fcr.2012.07.018
22. Guzmán C, Medina-Larqué AS, Velu G, González-Santoyo H, Singh RP, Huerta-Espino J, Ortiz-Monasterio I, Peña RJ (2014) Use of wheat genetic resources to develop biofortified wheat with enhanced grain zinc and iron concentrations and desirable processing quality. J Cereal Sci 60:617–622. https://doi.org/10.1016/j.jcs.2014.07.006
23. Bhati KK, Aggarwal S, Sharma S, Mantri S, Singh SP, Bhalla S, Kaur J, Tiwari S, Roy JK, Tuli R, Pandey AK (2014) Differential expression of structural genes for the late phase of phytic acid biosynthesis in developing seeds of wheat (Triticum aestivum L.). Plant Sci 224:74–85. https://doi.org/10.1016/j.plantsci.2014.04.009
24. Velu G, Crespo Herrera L, Guzman C, Huerta J, Payne T, Singh RP (2019) Assessing genetic diversity to breed competitive biofortified wheat with enhanced grain Zn and Fe concentrations. Front Plant Sci 9. https://doi.org/10.3389/fpls.2018.01971
25. Li BY, Zhou DM, Cang L, Zhang HL, Fan XH, Qin SW (2007) Soil micronutrient availability to crops as affected by long-term inorganic and organic fertilizer applications. Soil Tillage Res 96:166–173. https://doi.org/10.1016/j.still.2007.05.005
26. Khokhar JS, Sareen S, Tyagi BS, Singh G, Wilson L, King IP, Young SD, Broadley MR (2018) Variation in grain Zn concentration, and the grain ionome, in field-grown Indian wheat. PLoS One 13. https://doi.org/10.1371/journal.pone.0192026
27. Velu G, Singh RP, Joshi AK (2020) A decade of progress on genetic enhancement of grain zinc and iron in CIMMYT wheat germplasm. In: Wheat and barley grain biofortification. Elsevier, pp 129–138

28. Zhao FJ, Su YH, Dunham SJ, Rakszegi M, Bedo Z, McGrath SP, Shewry PR (2009) Variation in mineral micronutrient concentrations in grain of wheat lines of diverse origin. J Cereal Sci 49:290–295. https://doi.org/10.1016/j.jcs.2008.11.007
29. Cu ST, Guild G, Nicolson A, Velu G, Singh R, Stangoulis J (2020) Genetic dissection of zinc, iron, copper, manganese and phosphorus in wheat (Triticum aestivum L.) grain and rachis at two developmental stages. Plant Sci 291. https://doi.org/10.1016/j.plantsci.2019.110338
30. Hao Y, Velu G, Peña RJ, Singh S, Singh RP (2014) Genetic loci associated with high grain zinc concentration and pleiotropic effect on kernel weight in wheat (Triticum aestivum L.). Mol Breed 34:1893–1902. https://doi.org/10.1007/s11032-014-0147-7
31. Srinivasa J, Arun B, Mishra VK, Singh GP, Velu G, Babu R, Vasistha NK, Joshi AK (2014) Zinc and iron concentration QTL mapped in a Triticum spelta × T. Aestivum cross. Theor Appl Genet 127:1643–1651. https://doi.org/10.1007/s00122-014-2327-6
32. Velu G, Crossa J, Singh RP, Hao Y, Dreisigacker S, Perez-Rodriguez P, Joshi AK, Chatrath R, Gupta V, Balasubramaniam A, Tiwari C, Mishra VK, Sohu VS, Mavi GS (2016) Genomic prediction for grain zinc and iron concentrations in spring wheat. Theor Appl Genet 129:1595–1605. https://doi.org/10.1007/s00122-016-2726-y
33. Velu G, Singh RP, Crespo-Herrera L, Juliana P, Dreisigacker S, Valluru R, Stangoulis J, Sohu VS, Mavi GS, Mishra VK, Balasubramaniam A, Chatrath R, Gupta V, Singh GP, Joshi AK (2018) Genetic dissection of grain zinc concentration in spring wheat for mainstreaming biofortification in CIMMYT wheat breeding. Sci Rep 8. https://doi.org/10.1038/s41598-018-31951-z
34. Voss-Fels KP, Stahl A, Hickey LT (2019) Q&A: Modern crop breeding for future food security. BMC Biol. 17:1–7
35. Juliana P, Poland J, Huerta-Espino J, Shrestha S, Crossa J, Crespo-Herrera L, Toledo FH, Govindan V, Mondal S, Kumar U, Bhavani S, Singh PK, Randhawa MS, He X, Guzman C, Dreisigacker S, Rouse MN, Jin Y, Pérez-Rodríguez P, Montesinos-López OA, Singh D, Mokhlesur Rahman M, Marza F, Singh RP (2019) Improving grain yield, stress resilience and quality of bread wheat using large-scale genomics. Nat Genet 51:1530–1539. https://doi.org/10.1038/s41588-019-0496-6