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REVIEW ARTICLE

Agronomic biofortification of cereals with micronutrients: A systematic review

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Abstract

Micronutrient malnutrition is a global issue, particularly in developing regions of Asia and Africa, where a substantial portion of the population relies heavily on cereal grains as their staple food source. This deficiency arises due to an inadequate intake of essential micronutrients such as zinc and iron, in their daily diets. Biofortification offers a readily accessible and expedient solution for biofortifying cereal grains with these crucial micronutrients. This approach is particularly beneficial for the poorest rural communities. These populations often lack the means to afford mineral supplements or animal-derived products, which are typically richer sources of these micronutrients. From an agronomic biofortification perspective foliar application of zinc and iron fertilizers is considered more effective and requires lower quantities compared to soil application. For selenium (Se), both soil and foliar applications have been found to be effective with sodium selenate being more effective than selenite for soil applications. Even in scenarios where cultivars or genetically modified crops with inherently higher zinc and iron content in their grains are developed adequate fertilization with these micronutrients will still be necessary. Therefore, in the long run agronomic biofortification serves as a complementary approach to plant breeding and modern biotechnology aiming to increase the overall micronutrient content in the food supply. In this review, we will explore the synergistic role of agronomic biofortification alongside plant breeding and biotechnology, highlighting its potential to enhance the micronutrient density of staple crops and address global micronutrient malnutrition.

Keywords: biofortification; cereals; malnutrition; micronutrients; zinc

Introduction

Cereals play an essential role in global food production, with staple grains like wheat, rice and maize being cultivated extensively to support the world's food supply. These grains are fundamental components of diets worldwide and are grown on massive scales to meet the needs of billions of people (1). Cereal grains, the edible seeds of grasses, consist of the germ, endosperm and bran and can retain their nutritional value over long storage periods. They are rich in carbohydrates, proteins, dietary fibers, vitamins and minerals (2). Cereals contribute a significant part to human nutrition and are a vital source of energy for human diets (3). Wheat, barley, maize, oats, rice, rye and other cereals are extensively cultivated and processed into various staple foods consumed globally, making a significant contribution to energy, protein and nutrient intake for populations around the world. Throughout human history, cereals have played a pivotal role in the evolution of diets, facilitating the transition from hunter-gatherer societies to settled agricultural communities. In terms of market dynamics, cereals like maize, rice and wheat dominate global production and consumption trends, with projections indicating their continued importance in worldwide cereal markets. Overall, cereals are not only a dietary staple but also a cornerstone of agricultural economies and food security across nations.

Micronutrients are essential for the proper functioning, growth and development of both plants and humans. Globally, over two billion people suffer from micronutrient deficiencies, commonly referred to as "hidden hunger". Simultaneously, another two billion individuals are dealing with overweight or obesity. According to the FAO, undernutrition and inadequate micronutrient intake remain major contributors to the global disease burden. These issues highlight the double burden of malnutrition faced by many countries (3).

In agriculture, micronutrient deficiencies in crops reduce yield and nutritional value, ultimately affecting human health. Hidden hunger caused by poor dietary diversity and low nutrient density foods is particularly concerning in developing regions. Biofortification has emerged as a sustainable and cost-effective strategy to address these issues. It involves enhancing the micronutrient content of staple crops through conventional breeding or biotechnology (4). This approach offers long-term solutions for improving public health through improved crop nutrition. Approximately 792.5 million individuals globally suffer from malnutrition with 780 million residing in developing nations. The reliance on plant-based diets often low in bioavailable micronutrients like Fe, Zn, Se, I, carotenoids and folates worsens the issue (4). These micronutrients are crucial for the human growth and development as they play essential roles in various metabolic functions (4). In addition, overnutrition is becoming an increasingly serious issue the primary goal of our agricultural system has been to increase crop productivity and maximizing the grain yield rather than to advance human health. This strategy has caused a sharp increase in food grains vitamin deficiencies which has raised consumer micronutrient malnutrition. These days, the focus in agriculture is shifting from growing larger amounts of food crops to growing enough nutrient-rich food crops. This will aid in the fight against “Hidden hunger”. Hidden hunger is especially widespread in developing nations, particularly Sub-Saharan Africa and Southern Asia, due to overconsumption of staple foods, changes in dietary habits and inability to get appropriate nutrients due to poor political and economic status (5). India is where about half of the global population facing shortages of vital micronutrients resides, as reported by (Bayer Health in 2022) Biofortification stands out as a highly cost-effective solution to this issue, improving the nutritional content of crops, particularly in their edible parts, without compromising yields. Trials on biofortified crops have demonstrated a significant increase in the micronutrient levels compared to non-biofortified varieties. For instance, biofortified rice has been shown to contain 30 % more iron and 50 % more zinc than its conventional counterparts, significantly improving the nutritional quality of diets where these nutrients are deficient. Similarly, biofortified maize has exhibited a 40 % increase in provitamin A (beta-carotene) levels, benefiting populations at risk of vitamin A deficiency (6).

Effects of malnutrition in human population

Cereals, serve as staple food crops worldwide, often face the challenge of micronutrient deficiency due to their cultivation in soils lacking essential minerals such as zinc, iron, manganese and copper. This not only affects crop yield and quality but also poses a serious public health risk. Micronutrient malnutrition contributes to maternal mortality, low birth weight and increases the risk of chronic diseases such as diabetes and cardiovascular disorders (6). Furthermore, malnutrition can have detrimental effects on productivity, economic development and overall quality of life and poor health outcomes.

Zinc deficiency

Globally over two billion peoples are suffering from a lack of sufficient zinc in their diet condition which are critical for plants, animals and humans as it constitutes a vital component in numerous functional proteins. Zinc deficiency primarily arises from inadequate dietary intake, particularly from consuming cereal-based foods their poverty and cultural preferences, many rural populations rely heavily on cereal-based diets (7). Crop breeding primarily emphasizes improving the zinc content in grains and utilizing zinc fertilizers to increase zinc levels (7).

Recent research indicates that genetic modification of rice has enabled the attainment of approximately 30 % of the estimated average requirement of zinc in the human diet (8). Generally, foliar application of zinc proves to be effective during the late growth stages of plants (9). Foliar zinc application has been shown to significantly enhance zinc concentrations in cereal grains. Additionally, both soil application and foliar spraying of zinc sulphate ($ZnSO_4$) or zinc chelates have been demonstrated to increase grain zinc concentrations in plants, with effective zinc translocation through the phloem. Similarly, soil or foliar application of zinc can enhance zinc accumulation in leaves, tubers and fruit (10). Initially, farmers must be encouraged to adopt biofortification strategies for staple crops which involves using quality seeds and raising awareness about the importance of zinc nutrition for human health. This approach has the potential to increase the adoption of zinc fertilization (biofortification) techniques such as foliar spraying or combined foliar and soil application. Regardless of the growth stages, these methods aim to sustain yield while promoting the accumulation of accessible zinc in grains (11).

Iron deficiency

Iron deficiency leads to anaemia in over two billion individuals globally and elevating iron intake through dietary means could effectively combat this issue for the majority. While cereal grains typically possess low iron content, it's feasible to enhance iron levels while concurrently diminishing the concentration of antinutritional elements like phytate, thereby augmenting iron bioavailability (12). Similar observations have indicated that ancient wheat varieties contain higher micronutrient concentrations compared with modern era with an iron level ranging from 40 to 100 mg kg ha^{-1} (13). Iron has numerous important functions in the human body reflecting its ability to act as both an electron donor and acceptor. In this role, it forms the functional core of the heme complex, which is present in haemoglobin and myoglobin, the oxygen-binding molecules and the catalytic centre of cytochromes, which facilitate redox reactions. Consequently, iron is essential for oxygen transport within the body and for energy metabolism. Additionally, it contributes to the catalytic activity of various non-heme enzymes, such as ribonucleotide reductase.

The effectiveness of iron biofortification has been validated through real-world programs, such as the development and dissemination of iron-rich beans in Rwanda. This initiative, led by Harvest Plus and local partners, introduced bean varieties containing up to 80 % more iron than conventional varieties. These studies showed that regular consumption of these biofortified beans significantly improved iron status and cognitive performance, particularly in women and children. The program demonstrated not only the feasibility of breeding for enhanced micronutrient content but also the acceptability and scalability of biofortified crops in regions with high anaemia prevalence (14).

Iodine deficiency

Iodine is a crucial component of the thyroid hormones thyroxine and triiodothyronine, which control growth and development, as well as maintain the basal metabolic rate. However, while 30 % of the body's iodine is stored in the thyroid gland, the exact function of the remaining proportion distributed across other tissues remains unclear. This remaining iodine may have overlapping roles with other minerals such as selenium, iron, or zinc (14). Goiter is another significant symptom of iodine deficiency, resulting from the lack of thyroxine, which triggers the production of thyroid-stimulating hormone, consequently leading to an enlarged thyroid gland. India is among the countries most severely affected by this issue (15), with over 50 million cases of goiter and more than two million cases of cretinism, a severe form of iodine deficiency disorder affecting physical and mental development. To address this, India has implemented the Universal Salt Iodization (USI) program and recent estimates suggest that over 90 % of households now consume iodized salt, significantly reducing iodine deficiency disorders (15) with over 50 million cases of goiter and more than two million cases of cretinism, a severe form of iodine deficiency disorder affecting physical and mental development.

Selenium deficiency

Selenium is a crucial trace element which play a vital role in the proper functioning of humans, animals and certain primitive plant species, as it fulfils an essential micronutrient requirement for their overall well-being. and its supply in global food systems is highly variable. Selenium serves as an essential cofactor in approximately 50 enzymes, including antioxidant enzymes like glutathione peroxidase, whose function is to facilitate reduction reactions. It is also a cofactor for enzymes responsible for removing mineral ions from other proteins (16). Selenium functions as a cofactor in approximately 50 enzymes, including glutathione peroxidase, which is involved in antioxidant defense mechanisms. Deficiency in selenium has been linked to cardiovascular diseases and certain cancers (17).

Vitamin A deficiency

Vitamin A deficiency is a widespread issue globally, particularly impacting low-income and vulnerable communities in developing nations. It stands as a significant contributor to preventable blindness among children and has been linked to heightened susceptibility to severe infections like malaria, diarrhea and measles, often leading to increased mortality rates (18). According to WHO (2023), between 40-60 % of African children and 10-20 % of pregnant women in low-income countries suffer from this deficiency.

Scientists developed transgenic rice because cereals don't naturally contain β-carotene which humans can convert into vitamin A (19). This Transgenic rice is known as Golden Rice gets its name from the yellowish hue of its grains and provides β-carotene, easily converted into vitamin A. According to estimations, consuming a single cup of Golden Rice, a biofortified variety, could potentially provide approximately half of the daily recommended intake of vitamin A, fulfilling a substantial portion of the nutritional requirement for this essential micronutrient. This strategy has demonstrated significant promise in effectively tackling the lack of vitamin A and other essential micronutrients in developing nations, where millions of individuals are currently cultivating biofortified crops (20).

Biofortification

Biofortification, or biological fortification, refers to the process of improving the nutritional quality of food crops to address micronutrient deficiencies, also known as hidden hunger. This process strives to address micronutrient deficiencies, commonly referred to as hidden hunger by enhancing the consumption of vital nutrients like iron, vitamin A, zinc and other micronutrients particularly among populations with restricted access to varied diets or supplementation (20). The biofortification approach concentrates on optimizing the processes of nutrient uptake, translocation and accumulation within plants. This strategy aims to maximize the nutritional composition of crops, thereby mitigating malnutrition and promoting better human health outcomes. Research studies have illustrated the efficacy of these crops in enhancing the nutrient levels among vulnerable groups, such as women and children, who are at a higher risk of micronutrient deficiencies (21). This is achieved through the utilization of modern biotechnology techniques, conventional plant breeding methods and agronomic practices during cultivation (22). Among the various methods, agronomic biofortification is considered the most immediate and cost-effective for enhancing dietary micronutrient content (Table 1).

Approaches in biofortification

Biofortification the process of increasing the nutritional value of staple crops, can be achieved through various approaches. These include conventional plant breeding, agronomic practices and transgenic technologies. Conventional breeding focuses on the transfer of beneficial genes and quantitative trait loci (QTLs) to improve grain mineral concentrations (23). Additionally, agronomic practices, plant breeding techniques and transgenic approaches are utilized to biofortify a wide range of crops, including cereals, legumes, oilseeds, vegetables and fruits. The transgenic approach is particularly noteworthy for its sustainability and efficiency in biofortification efforts. These diverse approaches, ranging from traditional breeding methods to microbiological interventions,

Table 1. Crops currently undergoing a bio-fortification process with targeted nutrient range (μg/g) (22).

Crop	Biofortified varieties
Rice	CR Dhan 310, DRR Dhan 45, DRR Dhan 49, CR Dhan 315
Wheat	WB 02, HPBW01, Pusa Tejas (HI 8759), Pusa Ujala (HI 1605), MACS 4028, HI 8777, HI 1633, HD 3298, DBW 303, DDW 48
Maize	Pusa Vivek QPM9 improved, Pusa HM4 improved, Pusa HM9 improved, Quality Protein Maize Hybrid 1, Quality protein maize hybrid 2, Quality protein maize Hybrid 3, 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
Sorghum	Parbhani shakti

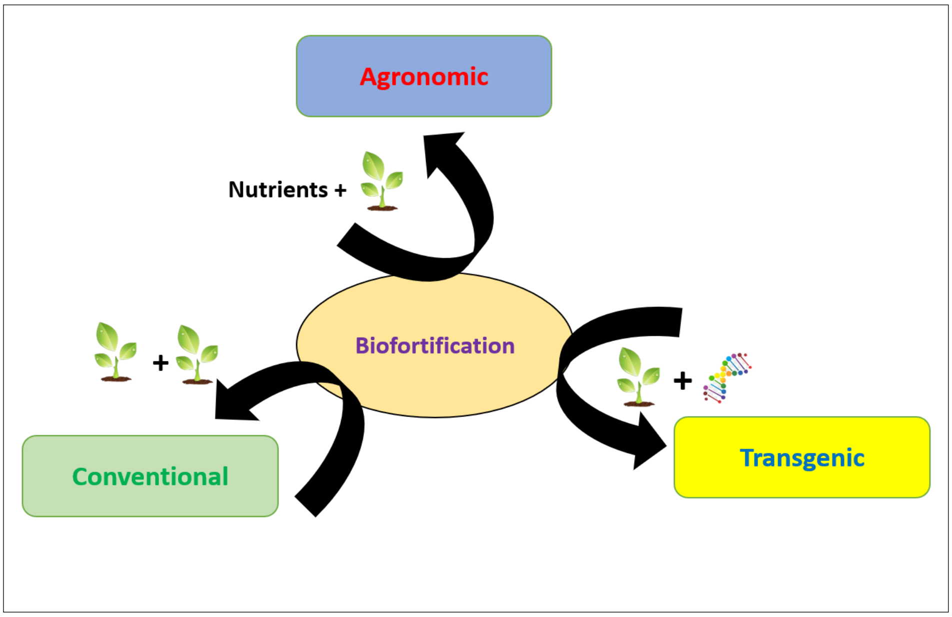

Fig. 1. Approaches in biofortification.

collectively contribute to addressing malnutrition and hidden hunger by increasing the nutritional content of staple crops, thereby benefiting vulnerable populations (24). Fig. 1 illustrates the approaches in biofortification.

Conventional breeding approaches

Conventional plant breeding, used for centuries, involves crossing plants with desirable traits either from improved cultivars or wild relatives-and selecting offspring that inherit those characteristics (25). Crop breeding for varieties with increased micronutrient content is crucial for biofortification effort aiming to address nutritional deficiencies, especially among rural populations. Leveraging genetic diversity within crop plants for enhancing micronutrient density represents an effective method, offering a sustainable solution with minimal recurring expenses (26). To accomplish this, it's essential to develop high-yielding cultivars with nutrient-dense traits and implement strategic breeding strategies tailored to specific nutritional requirements.

Combining conventional breeding with genetic engineering and agronomic practices proves to be more efficient than relying solely on conventional breeding methods. A notable example is the development of the semi-dwarf rice variety IR68144, enriched with iron (27). Enhancing vitamin A content in staple grains through conventional breeding poses challenges as existing rice varieties lack significant levels of this nutrient. Consequently, using traditional breeding methods to improve vitamin A is not possible. Provitamin A is synthesized exclusively in the green organs of plants and not in the seed's starchy storage part. The deficiency of vitamin A leads to approximately 4500 preventable child deaths (28). Therefore, Golden Rice, genetically engineered to produce provitamin A (β-carotene) in the rice endosperm, offers a promising solution to vitamin A deficiency in countries where rice is a major staple food. In the Philippines, human feeding trials confirmed that β-carotene from Golden Rice is efficiently converted into vitamin A, making it a viable dietary source of the nutrient (29). Further studies simulated the impact of Golden Rice in countries like Bangladesh, Indonesia and the Philippines, indicating that its adoption could significantly reduce the prevalence of vitamin A inadequacy among women and young children (30). In addition to Golden Rice, conventional breeding combined with transgenic strategies has been successfully employed to enhance iron and zinc content in rice varieties, offering a complementary approach to combat micronutrient deficiencies.

Transgenic approach

In contemporary times, genetic engineering stands out as a preferred alternative for biofortification in grains. This involves the introduction of desired genes from related organisms, overexpression of these genes, interference with gene silencing using RNAi and gene knockout via genome editing techniques. Fig. 2 describes the transgenic approach based on food groups. Through these transgenic methods, the functionality of genes can be characterized effectively. Additionally, when compared to agronomic and conventional plant breeding approaches, genetic engineering technologies are noted for their higher efficiency and reliability in studying the genotype-phenotype relationships of plants (31). As a result, a variety of transgenic methods have been experimented with and applied to increase the micronutrient content in cereal grains (32). For instance, multiple approaches have been utilized to enhance iron biofortification in rice.

Agronomic approach

Agronomic biofortification is considered the easiest and most cost-effective approach to enhance the micronutrient concentrations in food crops and address dietary deficiencies. Increasing the micronutrient content in staple crops, especially in cereal grains the application of micronutrient fertilizers, such as zinc and iron, can be done through soil or foliar (leaf) application, with varying effectiveness. Foliar application is highly effective for increasing the concentrations of iron, selenium, iodine and cobalt in crops. It is reported that applying micronutrients in combination with chelating agents like EDTA (ethylenediaminetetraacetic acid) can enhance their availability to plants and ultimately increase their concentration in seeds or grains. Zinc and iron biofortification are considered one of the

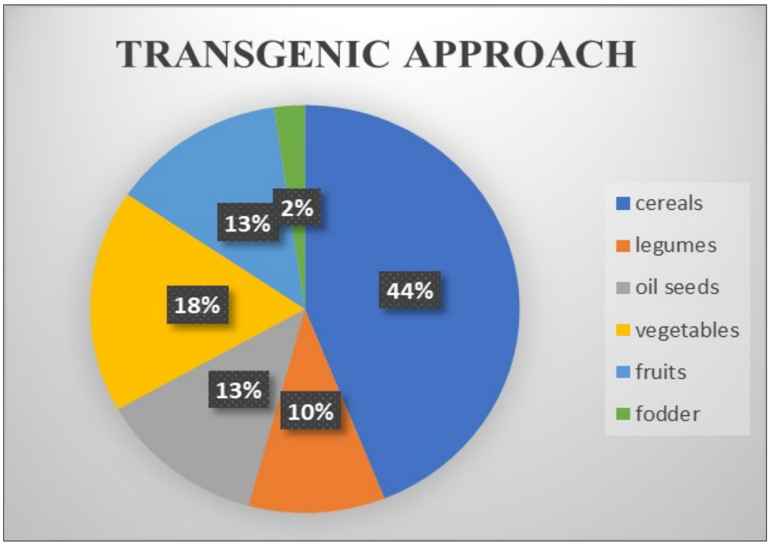

Fig. 2. Transgenic approach (60).

most effective and quickest strategies for reducing micronutrient deficiencies, particularly in cereal crops. The zinc fertilizers and the timing of foliar zinc application is crucial for maximizing the enhancement of zinc concentrations in grains (29). The application of zinc in the form of zinc-enriched urea (ZEU) to the soil not only improved the yield of rice and wheat crops but also enhanced the zinc concentration in their grains (30). Fig. 3 illustrates the different approach of agronomic biofortification.

When compared to other strategies, agronomic biofortification offers rapid results, scalability and adaptability across diverse environments. However, its effects are often transient, requiring repeated seasonal applications, which may not be feasible in low-income farming systems. In contrast, conventional breeding enables the development of biofortified cultivars with stable traits passed across generations, offering long-term sustainability, though the process is time-consuming and limited by the available genetic variability (31). Transgenic biofortification, such as in the case of Golden Rice, allows for precise insertion of target traits and can overcome genetic barriers, but faces high regulatory costs, ethical debates and public resistance (32). Thus, while agronomic approaches provide short-term solutions with high scalability, breeding offers sustainable, cost-effective outcomes over time and transgenic methods deliver the greatest precision but at the cost of complexity and adoption challenges.

Agronomic biofortification of rice

Rice is one of the staple food crops of the world population and it is extensively cultivated and distributed crop globally. Serving as the staple diet for over half of the world's populace, it also constitutes the primary source of dietary energy for regions like Asia and Southeast Asia, where rice consumption prevails. Following China, India ranks as the second-largest producer and consumer of rice. Rice is deficient in mineral nutrient such as zinc and iron is highlighting the immense need of biofortification in the rice crop. To enhance the zinc (Zn) content in cereals through biofortification, it is crucial to maintain an adequate level of plant-available Zn in the soil. While increasing the application rate of Zn fertilizers can potentially increase Zn uptake by the plants, this approach may not be economically viable as it would lead to an increase in the overall cost of cultivation (33). As an alternative approach, the use of synthetic chelates and/or foliar fertilization can be an effective and practical method for biofortification of cereals with zinc (Zn). These techniques can facilitate the efficient delivery of Zn to the plants without any risk. Application of zinc to soil as fertilizer

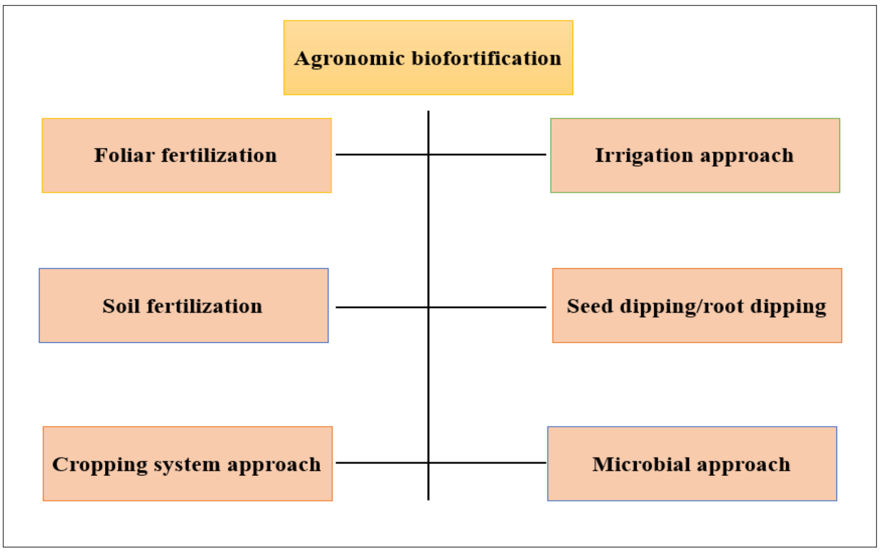

Fig. 3. Different approaches of agronomic biofortification.

in addition to foliar spraying proves to be an effective technique for growing the zinc grain content of rice grown in soil (34). The timing of foliar zinc (Zn) fertilizer application plays a crucial role in determining its effectiveness for biofortification. Applying foliar Zn fertilizers during the later stages of crop development is particularly beneficial in enriching the grains with zinc content. Although the iron concentration in grains is relatively low compared to iron from meat sources. When addressing iron deficiency in rice, among various inorganic iron carriers, $FeSO_4.7H_2O$ stands out as the most utilized fertilizer (35).

The maximum concentration of iron (Fe) was reported in PR113 and PR116 cultivars when 0.5 % and 1 % levels of $FeSO_4 \cdot 7H_2O$ spray were applied for iron fortification at the maximum tillering stage (36). A significant average increase of 15 % in iron (Fe) concentration was observed with the application of nitrogen (N) ranging from 0 to 135 kg ha^{-1}, indicating a positive correlation between nitrogen application and the enhancement of iron levels (37). For rice, selenium-enriched fertilizers are used as soil and foliar applications to enhance the selenium concentration in the crop (38). When compared to foliar application, applying selenium to the soil introduces additional factors like adsorption to soil colloids, leading to reduced selenium availability for plants; therefore, the method, form and timing of application play a pivotal role in achieving successful biofortification in cereal crops (37).

Agronomic biofortification of wheat

Wheat holds significant importance in ensuring global food security and human nutrition, serving as a staple for approximately 35 % of the world's population. However, it naturally contains low levels of zinc and frequent consumption of wheat-based foods can result in zinc deficiency among humans (38). Applying the recommended doses of nitrogen (N) and potassium (K) from fertilizer sources to wheat plants led to increased concentrations of zinc (Zn) and iron (Fe) in both grain and straw compared to various control groups (39). In wheat, the application of both soil and foliar zinc led to increased zinc concentration in grain and shoot compared to when zinc was applied solely to the soil, seed, or foliage. Foliar application of zinc, especially during the later growth stages such as the early milk and dough stages, proved to be the most effective method for enhancing zinc concentration in both the whole grain and endosperm of wheat, whereas soil application was the least effective (40). Although combined soil and foliar application of zinc showed better performance than foliar application alone at two specific locations, it was not consistently more effective overall (41).

Iron plays crucial roles in various processes essential for plant growth and development. These include synthesizing chlorophyll, facilitating respiration and photosynthesis. Additionally, iron serves as a vital component in numerous plant enzymes, aiding in oxidation and the release of energy during the breakdown of carbohydrates and nucleic acids (42). Plants grown in soils lacking sufficient iron are known to exhibit low iron content in their edible parts, leading to iron deficiency in humans who consume them (43). Foliar application of $FeSO_4$ or iron chelates in wheat was found to increase grain iron concentration by no more than 36 %. In contrast, increasing nitrogen application to the soil significantly enhanced iron concentrations in both wheat shoots and grains (44). Similarly, foliar application of urea has also been reported to increase iron content in grains.

Monitoring and optimizing selenium concentrations in wheat is crucial due to significant variations across countries and regions. This is essential to prevent both selenium deficiency and toxicity (45). The foliar application of selenium for biofortification is more efficient due to its direct uptake by the plant through the leaves, eliminating the need for selenium to be transported from the roots to the shoots, a process that can be inefficient. Furthermore, this method reduces the risk of selenium being sequestered by the soil, as it is applied directly to the foliage (46). A widely applied strategy to combat micronutrient deficiencies in humans is agronomic biofortification, which involves increasing the concentration of essential micronutrients in the crops.

Agronomic biofortification of maize

In India, maize holds a significant position in the agricultural landscape. Representing the third most crucial cereal crop after wheat and rice, it is called "queen of cereals" and "miracle crop" owing to its remarkable productivity compared to other cereals (47). With its adaptability to both tropical and temperate climates worldwide, maize plays a pivotal role as a staple food and livestock feed. Notably, in India, 45 % of the maize production is consumed directly as a staple food in various forms, underlining its importance in the diets of many people across the nation (48). Maize is one of the popular cereal crops due to its diverse functionality as source of food for humans and animals as well Maize is a nutrient-intensive crop that demands a significant supply of both macronutrients and micronutrients, especially zinc, to achieve optimal yields (49). Zinc concentrations in maize grain can be increased using agronomic strategies of soil application or seed priming and that the crop responds to Zn fertilization (50). The combined application of zinc fertilizers to both soil and foliar application under field conditions proves to be a highly effective and practical approach to maximize zinc uptake and accumulation in the entire maize grain, as well as increasing the overall yield, compared to employing a single fertilization method alone (51). Applying foliar zinc spray along with either broadcasting or banding zinc fertilizer notably increases both crop yield and the zinc concentration in grains (52). The application of foliar zinc spraying concurrently enhanced the levels and accessibility of zinc and increases iron content in maize grains to some degree. Employing foliar nutrient application serves as a rapid and effective method to enhance the nutritional profile of the crop (53).

The application of farmyard manure (FYM) enriched with varying concentrations of $ZnSO_4$ and $FeSO_4$ resulted in elevated levels of zinc and iron in maize grains. The gradual release of nutrients into the soil solution promotes enhanced nutrient absorption and mitigates the risk of nutrient leaching losses. The selenium (Se) also play an important role in human and animal health in worldwide and it has also been increased by applying fertilization as an effective agronomic biofortification strategy (54).

Agronomic biofortification of sorghum

Sorghum (*Sorghum bicolor* (L.) is cultivated across over 40 million hectares worldwide, yielding approximately 65 million tonnes, this crop plays a vital role in ensuring food security in West Africa, serving as a staple food (55). Moreover, it holds significant importance as a food crop in the semiarid regions of Sub-Saharan Africa (SSA) and South Asia (56). Agronomic biofortification, which involves increasing the levels of iron and zinc in sorghum grains by applying fertilizers containing these minerals, particularly in post rainy sorghum varieties, emerges as a cost-effective strategy to combat hidden hunger prevalent in regions where sorghum is a primary dietary staple, such as the semi-arid tropics (57). Incorporating zinc-enriched fertilizers into the soil facilitates greater zinc absorption by the sorghum crop, consequently enhancing the bioavailability of zinc in the edible parts of the plant (58). The concentration of zinc and iron in grains has been enhanced by the application of biofertilizers along with inorganic fertilizers and vermicompost.

Future aspects of biofortification

Micronutrient deficiencies remain a critical global issue, undermining food security, human health and economic development, especially in low-resource regions. Fertilizer-based biofortification presents a forward-looking solution by enhancing the nutrient content of staple crops (59). However, widespread implementation faces several barriers. The high cost of micronutrient-enriched fertilizers, containing elements like zinc, iron and boron, remains a significant hurdle for small-scale farmers (60). To address this, future strategies should involve policy support through subsidies and incentives from governments and international organizations to improve affordability and accessibility. Equally important are educational campaigns that inform farmers about the long-term economic benefits, including improved yields and soil health, which could encourage adoption of these practices (61).

Technological and infrastructural limitations also hinder progress. In many rural areas, poor fertilizer production and distribution networks restrict access. To overcome this, investments must be directed toward improving infrastructure and supply chains (62). Research and innovation will play a pivotal role in developing next-generation fertilizers that enhance micronutrient bioavailability. Emerging technologies such as nanotechnology and precision agriculture can ensure efficient delivery, minimize waste and reduce environmental risks (63). Moving forward, it will be vital to train farmers in responsible fertilizer use and implement clear guidelines to prevent soil degradation and nutrient runoff. Sustainable implementation of fertilizer-based biofortification will be key to its success, ensuring environmental safety while addressing malnutrition on a global scale.

Conclusion

Agronomic biofortification presents a promising approach to address micronutrient deficiencies in major cereal crops. Through strategies like soil nutrient management and optimized crop practices, significant strides have been made in maximizing the nutritional quality of staple cereal grains. However, several key challenges remain to be addressed, including the need for further research to refine biofortification strategies, ensure the sustainability and mitigate potential environmental impacts. Overcoming these obstacles will require collaborative efforts from researchers, policymakers, agricultural experts and local communities. Continued investments and support are critical to fully unlock the benefits of biofortified cereals in combating malnutrition and promoting global food security and human health. With concerted efforts and commitment agronomic biofortification can play a vital role in improving nutrition and well-being worldwide.

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Authors' contributions

ED collected the literature and drafted the manuscript, while SJ provided overall guidance for corrections and improvements. TR, AG, SM, PS and SE assisted with literature collection and formatting. All authors contributed equally to revising the manuscript and approved the final draft.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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