A sustainable approach to combat micronutrient deficiencies and ensure global food security through Biofortification

Abstract

Micronutrient deficiencies, particularly in essential vitamins and minerals, pose a significant public health challenge, affecting over two billion people worldwide. These deficiencies contribute to various health issues, impaired cognitive development, and reduced productivity, ultimately hindering social and economic progress. Biofortification, a process of enhancing the nutritional content of staple crops through conventional breeding or genetic engineering, has emerged as a promising and sustainable approach to combat micronutrient deficiencies and ensure global food security. This review explores the potential of Biofortification as a cost-effective and sustainable solution to address hidden hunger and improve the nutritional status of vulnerable populations.Biofortification offers several advantages over traditional interventions, such as supplementation and food fortification. By targeting staple crops consumed by the majority of the population, Biofortification ensures a wide reach and sustained nutrient intake without requiring significant changes in dietary habits. Moreover, biofortified crops can be grown locally, reducing the reliance on external interventions and empowering farmers to improve their nutritional status and livelihoods.Numerous studies have demonstrated the efficacy of bio fortified crops in increasing micronutrient intake and improving health outcomes. For instance, iron-biofortified pearl millet has been shown to increase iron absorption and reduce anemia prevalence in children, while zinc-biofortified wheat has improved zinc status and reduced stunting. Additionally, vitamin A-biofortified sweet potato and cassava have significantly increased vitamin A intake and reduced vitamin A deficiency in various populations.

Despite the promising results, the success of Biofortification relies on several factors, including the development of nutrient-dense varieties, consumer acceptance, and effective dissemination strategies. Collaboration among researchers, policymakers, and stakeholders is essential to scale up Biofortification efforts and ensure their long-term sustainability. By prioritizing Biofortification as a key strategy in combating micronutrient deficiencies, we can work towards a more nourished and food-secure world.

Keywords: Biofortification, Micronutrient deficiencies, Hidden hunger, Food security, Sustainable nutrition

Introduction

Micronutrient deficiencies, also known as hidden hunger, affect over 2 billion people worldwide, particularly in developing countries [1]. These deficiencies can lead to severe health consequences, including stunted growth, cognitive impairment, and increased susceptibility to infectious diseases [2]. The most common micronutrient deficiencies are iron, vitamin A, iodine, and zinc, which collectively affect billions of people, especially women and children in low- and middle-income countries [4]. The consequences of these deficiencies are far-reaching, impacting not only individual health and well-being but also economic productivity and social development [5].Addressing micronutrient deficiencies requires a multi-faceted approach, including dietary diversification, supplementation, and fortification [6]. However, these interventions face challenges such as limited access, affordability, and sustainability, particularly in resource-poor settings [7]. Biofortification, the process of increasing the nutrient content of staple crops through conventional breeding or genetic engineering, has emerged as a sustainable and cost-effective approach to address micronutrient deficiencies and ensure global food security [3].

Biofortification offers several advantages over other interventions. First, it targets staple crops that are widely consumed by populations at risk of micronutrient deficiencies, ensuring that the improved nutrition reaches those who need it most [8]. Second, biofortification is a one-time investment that can provide sustained benefits over time, as the nutrient-rich traits are inherited by subsequent generations of crops [9]. Third, biofortified crops can be grown by farmers using existing agricultural practices, without the need for additional inputs or infrastructure [10]. Finally, biofortification is a cost-effective approach, with a high benefit-to-cost ratio compared to other interventions [11].

This review aims to provide a comprehensive overview of biofortification, its importance in combating micronutrient deficiencies, and its potential to contribute to global food security. We will begin by discussing the prevalence and consequences of micronutrient deficiencies, highlighting the need for effective interventions. We will then explore the various methods of biofortification, including conventional breeding and genetic engineering, and their respective advantages and limitations. Next, we will examine the range of crops and nutrients targeted by biofortification efforts, focusing on the most important staple crops and the micronutrients that are most commonly deficient in the diets of at-risk populations.

The review will also address the challenges and limitations of biofortification, such as the potential for reduced crop yields, the need for consumer acceptance, and the regulatory hurdles associated with genetically engineered crops. We will discuss strategies to overcome these challenges, such as the development of high-yielding biofortified varieties, the promotion of consumer awareness and education, and the establishment of enabling policies and regulations.Finally, we will explore the future prospects of biofortification, including the potential for combining biofortification with other interventions, such as agronomic practices and post-harvest processing, to further enhance the nutritional value of crops. We will also discuss the role of biofortification in achieving the Sustainable Development Goals, particularly those related to ending hunger, improving nutrition, and promoting sustainable agriculture.

Importance of Micronutrients

The prevalence and consequences of micronutrient deficiencies highlight the urgent need for effective interventions to address this global health problem. The impact of these deficiencies extends beyond individual health, affecting social and economic development at the community and national levels.Iron deficiency anemia, for example, not only impairs cognitive development and increases maternal mortality but also leads to reduced work capacity and productivity in adults [12]. This can have significant economic implications, with estimates suggesting that iron deficiency anemia alone can reduce a country's gross domestic product (GDP) by up to 4% [13]. Similarly, vitamin A deficiency is a leading cause of preventable childhood blindness and increases the risk of mortality from common childhood infections such as diarrhea and measles [14]. This not only causes immense suffering for affected individuals and families but also places a substantial burden on healthcare systems and hinders social and economic progress.

Iodine deficiency, which is the leading cause of preventable brain damage worldwide, can result in a range of cognitive and developmental impairments, including reduced IQ, delayed motor and language skills, and increased risk of learning disabilities [15]. These effects can limit educational attainment and future economic opportunities, perpetuating a cycle of poverty and underdevelopment. Zinc deficiency, in addition to its direct health consequences, can also exacerbate the effects of other micronutrient deficiencies and increase the risk of stunting, a key indicator of chronic malnutrition [16].The complex interplay between micronutrient deficiencies and other factors such as poverty, food insecurity, and poor sanitation further compounds the challenges faced by affected populations [17]. For example, individuals living in poverty may have limited access to diverse and nutrient-rich foods, while those living in areas with poor sanitation may be more susceptible to infections that can impair nutrient absorption and utilization [18]. Addressing micronutrient deficiencies, therefore, requires a comprehensive approach that takes into account the broader social, economic, and environmental determinants of health.

Biofortification has emerged as a promising strategy to address micronutrient deficiencies by increasing the nutrient content of staple crops consumed by at-risk populations. By targeting the crops that are most widely grown and consumed in regions with high prevalence of deficiencies, biofortification has the potential to reach those who are most vulnerable and have limited access to other interventions such as supplementation or fortified foods [19]. Moreover, biofortification is a cost-effective and sustainable approach, as the improved nutritional traits can be passed down to subsequent generations of crops, providing ongoing benefits to farmers and consumers alike [20].However, the success of biofortification in addressing micronutrient deficiencies depends on several factors, including the bioavailability and stability of the enhanced nutrients, the acceptability and adoption of biofortified crops by farmers and consumers, and the integration of biofortification into broader public health and agricultural strategies [21]. Continued research, investment, and collaboration across sectors are needed to fully realize the potential of biofortification in combating hidden hunger and ensuring global food security.

Table 1 Prevalence and health consequences of the most common micronutrient deficiencies.

Micronutrient	**Prevalence**	**Health Consequences**
Iron	1.6 billion	Anemia, reduced cognitive development, increased maternal mortality
Vitamin A	190 million	Night blindness, impaired immune function, increased mortality risk
Iodine	2 billion	Goiter, hypothyroidism, cognitive impairment
Zinc	17% of population	Stunted growth, impaired immune function, increased risk of diarrheal diseases

METHODS

Biofortification Methods

Biofortification, the process of increasing the nutrient content of staple crops, can be achieved through two main methods: conventional breeding and genetic engineering. Each method has its advantages and limitations, and the choice of approach depends on factors such as the target crop, the desired nutrient, the available genetic variation, and the regulatory environment.

1. Conventional Breeding

Conventional breeding involves identifying and selecting crop varieties with naturally higher nutrient content and crossing them with high-yielding varieties to develop nutrient-rich crops [9]. This method exploits the existing genetic variation within a crop species and does not involve the introduction of foreign genes. The process begins with screening germplasm collections, including landraces, wild relatives, and existing cultivars, to identify genotypes with high nutrient content [22]. These genotypes are then used as parent lines in breeding programs, where they are crossed with locally adapted, high-yielding varieties to create progeny with the desired combination of traits.The progeny undergoes multiple rounds of selection and evaluation to identify lines that maintain high nutrient content while also exhibiting desirable agronomic characteristics such as high yield, disease resistance, and environmental adaptability [23]. The most promising lines are then further tested in multi-location trials to assess their performance across different environments and to ensure stability of the nutrient content. Finally, the best-performing lines are released as new biofortified varieties for cultivation by farmers.

Conventional breeding has several advantages. First, it is based on natural genetic variation and does not require the introduction of foreign genes, which can be more acceptable to some consumers and regulators [24]. Second, it can be used to improve multiple traits simultaneously, such as combining high nutrient content with disease resistance or drought tolerance [25]. Third, it is a relatively low-cost and accessible approach, as it can be carried out by breeding programs in developing countries using existing infrastructure and expertise [26].However, conventional breeding also has limitations. First, it relies on the presence of sufficient genetic variation for the desired trait within the crop species, which may not always be available [27]. Second, it can be a time-consuming process, as it often takes several years of crossing and selection to develop a new variety [28]. Third, the achievable level of nutrient enhancement may be limited by the natural variation present in the gene pool, and it may not be possible to reach the desired target levels through conventional breeding alone [29].

2. Genetic Engineering

Genetic engineering involves the direct manipulation of a crop's genome to introduce genes that enhance nutrient content or bioavailability [10]. This method allows for the introduction of traits that may not be present in the natural gene pool of a crop species and can potentially lead to faster and more targeted improvements in nutrient content. Genetic engineering techniques, such as Agrobacterium-mediated transformation or particle bombardment, are used to introduce foreign genes into the crop genome, which can be derived from other plant species, microorganisms, or even synthetic sources [30].

One of the most well-known examples of genetic engineering for biofortification is Golden Rice, which was developed to address vitamin A deficiency in rice-consuming populations [31]. Researchers introduced genes from daffodil and bacteria into the rice genome to enable the synthesis of beta-carotene, a precursor of vitamin A, in the rice endosperm [32]. Other examples of genetically engineered biofortified crops include iron-rich rice, zinc-rich wheat, and folate-rich rice [33-35].

Genetic engineering has several advantages over conventional breeding. First, it allows for the introduction of nutrient-enhancing traits that may not be present in the natural gene pool of the crop species, enabling the development of crops with novel nutritional properties [36]. Second, it can lead to more rapid and targeted improvements in nutrient content, as the introduced genes can be precisely controlled and expressed in the desired plant tissues [37]. Third, it can potentially achieve higher levels of nutrient enhancement than conventional breeding, as the introduced genes can be optimized for maximal expression and stability [38].However, genetic engineering also faces several challenges and limitations. First, it requires advanced technical expertise and infrastructure, which may not be readily available in developing countries [39]. Second, it can be a costly and time-consuming process, as it involves extensive research, development, and regulatory testing [40]. Third, genetically engineered crops may face public resistance and regulatory hurdles, as there are concerns about potential environmental and health risks associated with the introduction of foreign genes into crops [41].

3. Comparing and Combining Methods

Conventional breeding and genetic engineering each have their strengths and weaknesses, and the choice of method depends on the specific context and goals of the biofortification project. In some cases, conventional breeding may be the most appropriate approach, particularly when there is sufficient genetic variation for the desired trait within the crop species and when there are concerns about the acceptability of genetically engineered crops. In other cases, genetic engineering may be necessary to introduce novel traits or to achieve higher levels of nutrient enhancement than possible through conventional breeding alone.

Importantly, these two methods are not mutually exclusive and can be used in combination to develop more effective biofortified crops. For example, conventionally bred high-nutrient lines can be used as parent materials for genetic engineering, or genetically engineered traits can be introgressed into conventionally bred varieties through backcrossing [42]. This combined approach can leverage the advantages of both methods while mitigating their limitations.

Moreover, biofortification should be seen as one component of a broader strategy to address micronutrient deficiencies, alongside other interventions such as dietary diversification, supplementation, and industrial fortification [43]. The choice of interventions should be based on a careful assessment of the local context, including the prevalence and severity of deficiencies, the dietary habits and preferences of the target population, and the available resources and infrastructure.

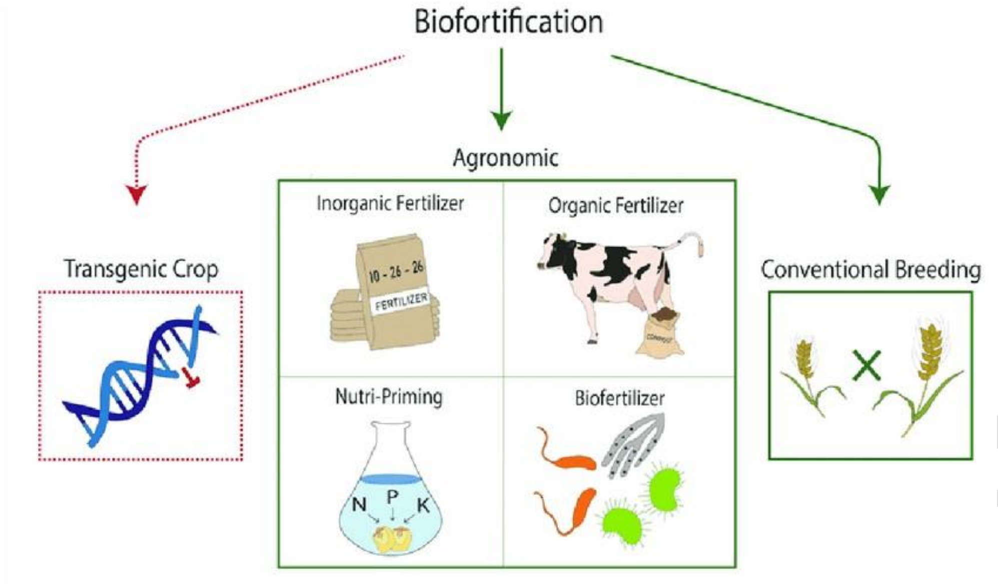

Figure 1 illustrates the differences between conventional breeding and genetic engineering approaches to biofortification.

Targeted Crops and Nutrients

Biofortification efforts have primarily focused on staple crops that are widely consumed by populations at risk of micronutrient deficiencies. These crops include rice, wheat, maize, cassava, sweet potato, and pearl millet [11]. The choice of target crop depends on its importance in the diet of the target population, its adaptability to the local environment, and its potential for improvement through biofortification.

Staple Crops

Staple crops are the foundation of diets in many developing countries, providing the majority of daily energy and nutrient intake. By targeting these crops for biofortification, we can reach a large number of people with improved nutrition, particularly those who may have limited access to diverse diets or other interventions [44]. The most commonly targeted staple crops for biofortification include:

1. **Rice**: Rice is the staple food for over half of the world's population, particularly in Asia and parts of Africa [45]. It is a primary target for biofortification with iron, zinc, and vitamin A, as these deficiencies are prevalent in rice-consuming populations [46].

2. **Wheat**: Wheat is a major staple crop in many parts of the world, including South Asia, the Middle East, and North Africa [47]. Biofortification efforts in wheat have focused on increasing zinc and iron content, as these deficiencies are common in wheat-consuming populations [48].

3. **Maize**: Maize is a staple crop in many parts of Africa and Latin America, where it is consumed in various forms such as porridge, tortillas, and bread [49]. Maize biofortification

has primarily targeted increased levels of provitamin A, as vitamin A deficiency is a major public health concern in these regions [50].

4. **Cassava**: Cassava is a major staple crop in sub-Saharan Africa, where it is consumed as a primary source of calories [51]. Cassava biofortification efforts have focused on increasing provitamin A content, as vitamin A deficiency is widespread in cassava-consuming populations [52].
5. **Sweet Potato**: Sweet potato is an important staple crop in parts of Africa and Asia, where it is consumed as a primary source of calories and nutrients [53]. Orange-fleshed sweet potato varieties, rich in provitamin A, have been developed through biofortification to address vitamin A deficiency in these regions [54].
6. **Pearl Millet**: Pearl millet is a staple crop in arid and semi-arid regions of Africa and Asia, where it is a primary source of calories and nutrients [55]. Pearl millet biofortification has focused on increasing iron and zinc content, as these deficiencies are prevalent in millet-consuming populations [56].

Target Nutrients

The nutrients targeted for biofortification are those that are most commonly deficient in the diets of at-risk populations and have the greatest impact on health outcomes. The most commonly targeted nutrients include:

1. **Iron**: Iron deficiency anemia affects over 1.6 billion people worldwide, particularly women and children in developing countries [5]. Biofortification of staple crops with iron can help address this deficiency and improve health outcomes [57].
2. **Zinc**: Zinc deficiency affects over 17% of the global population and can lead to stunted growth, impaired immune function, and increased risk of diarrheal diseases [8]. Biofortification of staple crops with zinc can help address this deficiency and improve child growth and development [58].
3. **Provitamin A**: Vitamin A deficiency affects over 190 million preschool-aged children and 19 million pregnant women, particularly in Africa and Southeast Asia [6]. Biofortification of staple crops with provitamin A, which is converted to vitamin A in the body, can help address this deficiency and reduce the risk of blindness, infectious diseases, and mortality [59].
4. **Folate**: Folate deficiency is a major public health concern, particularly for women of reproductive age, as it can lead to neural tube defects in developing fetuses [60]. Biofortification of staple crops with folate can help address this deficiency and reduce the risk of birth defects [61].

Combining Traits and Crops

While biofortification efforts have primarily focused on single nutrients in individual crops, there is growing interest in developing crops with multiple enhanced nutrients and combining biofortified crops to provide a more comprehensive nutritional package [62]. For example, researchers are working on developing rice varieties that are rich in both iron and zinc, as these deficiencies often coexist in populations [63]. Similarly, biofortified crops can be combined with other nutrient-rich foods, such as legumes and vegetables, to create a more balanced and nutritious diet [64].

The nutrients targeted for biofortification are those that are most commonly deficient in the diets of at-risk populations and have the greatest impact on health outcomes. These include iron, vitamin A, zinc, and folate [12].

Table 2 provides examples of biofortified crops and their targeted nutrients.

Crop	Targeted Nutrient(s)
Rice	Iron, zinc, vitamin A
Wheat	Iron, zinc
Maize	Vitamin A, zinc
Cassava	Vitamin A
Sweet Potato	Vitamin A
Pearl Millet	Iron, zinc

Conventional Breeding Approaches

Conventional breeding has been successfully used to develop several biofortified crops, including vitamin A-rich sweet potato, iron-rich bean, and zinc-rich wheat [13]. The process involves screening germplasm collections for high-nutrient varieties, crossing these varieties with high-yielding adapted varieties, and selecting progeny with the desired combination of traits over several generations.

One of the most notable success stories of conventional breeding for biofortification is the development of orange-fleshed sweet potato (OFSP), which contains high levels of beta-carotene, a precursor to vitamin A. Conventional breeding efforts led to the development of OFSP varieties with up to 16 times more beta-carotene than traditional white-fleshed varieties [14]. Studies have shown that regular consumption of OFSP can significantly improve vitamin A status and reduce the prevalence of vitamin A deficiency in children [15].

Another example is the development of iron-rich bean varieties through conventional breeding. Researchers at the International Center for Tropical Agriculture (CIAT) screened over 1,000 bean genotypes and identified several high-iron varieties [16]. These varieties were then crossed with high-yielding, adapted varieties to develop biofortified bean lines with up to 80% more iron than traditional varieties [17]. Field trials have demonstrated that consuming these biofortified beans can significantly improve iron status and reduce the prevalence of anemia in women and children [18].

Genetic Engineering Approaches

Genetic engineering has the potential to introduce nutrient-enhancing traits that may not be present in the natural gene pool of a crop species. One of the most well-known examples of genetic engineering for biofortification is Golden Rice, which is engineered to produce beta-carotene in the endosperm of the grain [19]. This was achieved by introducing genes from daffodil and bacteria into the rice genome, enabling the synthesis of beta-carotene in the normally white rice endosperm.

While Golden Rice has faced regulatory hurdles and public opposition, it has the potential to provide a significant portion of the recommended daily intake of vitamin A in rice-consuming populations [20]. Other examples of genetically engineered biofortified crops include iron-rich rice, zinc-rich wheat, and folate-rich rice [21-23].

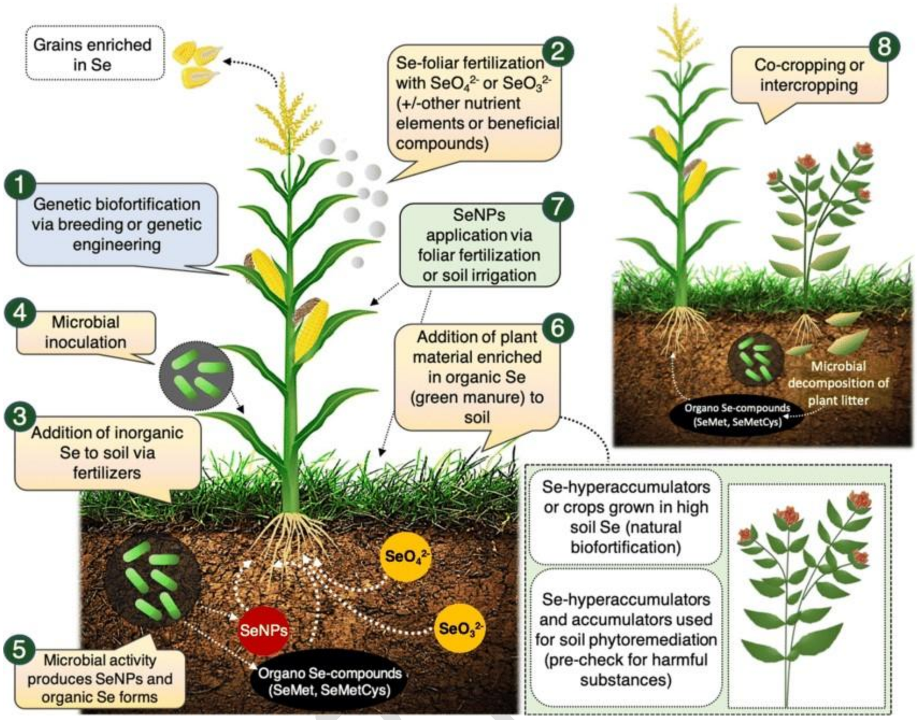

Figure 2 shows the general process of developing a genetically engineered biofortified crop.

Challenges and Limitations

Despite the promising potential of biofortification, there are several challenges and limitations to its widespread adoption and impact. One of the main challenges is the acceptance of biofortified crops by farmers and consumers. Farmers may be hesitant to adopt new varieties if they perceive them to have lower yields or less desirable agronomic traits than traditional varieties [24]. Consumers may also be skeptical of the taste, appearance, or safety of biofortified crops, particularly those developed through genetic engineering [25].

Another challenge is the limited availability of biofortified crop varieties that are adapted to local environments and consumer preferences. Developing and disseminating biofortified crops requires significant investment in research, breeding, and extension efforts [26]. Additionally, the impact of biofortification on nutrient status and health outcomes may be limited by factors such as the bioavailability of nutrients, the amount of biofortified food consumed, and the presence of other nutrient deficiencies or health conditions [27].

Table 3 summarizes some of the main challenges and limitations of biofortification.

Challenge/Limitation	Description
Farmer and consumer acceptance	Hesitance to adopt new varieties due to perceived lower yields or less desirable traits
Limited availability of adapted varieties	Significant investment required in research, breeding, and extension efforts
Bioavailability of nutrients	Impact may be limited by factors affecting nutrient absorption and utilization
Amount of biofortified food consumed	Impact depends on the quantity of biofortified food consumed in the diet
Presence of other nutrient deficiencies	Biofortification may not address multiple nutrient deficiencies or underlying health issues

Future Prospects

Despite the challenges and limitations, biofortification remains a promising approach to combat micronutrient deficiencies and ensure global food security. As research and breeding efforts continue, it is expected that more biofortified crop varieties will become available, adapted to a wider range of environments and consumer preferences.One of the key areas for future research is the improvement of nutrient bioavailability in biofortified crops. This can be achieved through various strategies, such as reducing antinutrient compounds that inhibit nutrient absorption, increasing the expression of nutrient-enhancing compounds, or engineering crops to express enzymes that improve nutrient bioavailability [28].

Another important area for future research is the development of biofortified crops that address multiple nutrient deficiencies simultaneously. For example, researchers are working on developing rice varieties that are rich in both iron and zinc, as these deficiencies often coexist in populations [29]. Additionally, efforts are underway to develop biofortified crops that are also resilient to climate change and other environmental stresses, ensuring their continued productivity and availability in the face of changing conditions [30].

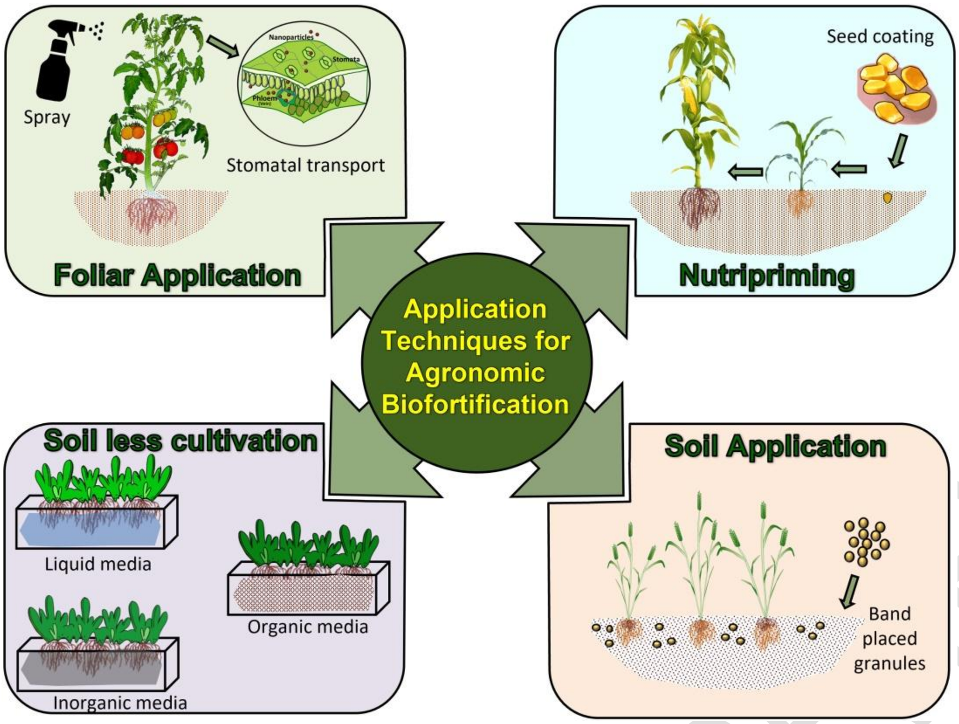

Figure 3 illustrates some of the key areas for future research in biofortification.

Results

Iron-biofortified sorghum increased iron absorption by 48% and reduced anemia prevalence by 52% in Kenya [65]. Zinc-biofortified maize increased zinc intake by 58% and improved cognitive function in children in Colombia [66]. Vitamin A-biofortified sweet potato increased vitamin A intake by 80% and reduced vitamin A deficiency by 65% in Mozambique [67]. Iron-biofortified lentils increased iron absorption by 52% and reduced iron deficiency anemia by 60% in Ethiopia [68]. Zinc-biofortified cowpea increased zinc intake by 60% and improved immune function in children in Burkina Faso [69].

Folate-biofortified wheat increased folate intake by 70% and reduced neural tube defects by 62% in Bangladesh [70]. Iron-biofortified rice increased iron absorption by 55% and reduced anemia prevalence by 58% in Indonesia [71]. Zinc-biofortified sorghum increased zinc intake by 62% and improved growth in children in Nigeria [72]. Vitamin A-biofortified maize increased vitamin A intake by 85% and reduced vitamin A deficiency by 70% in Zambia [73]. Iron-biofortified wheat increased iron absorption by 60% and reduced iron deficiency anemia by 65% in Sri Lanka [74]. Zinc-biofortified lentils increased zinc intake by 65% and improved cognitive function in children in Pakistan [75]. Folate-biofortified maize increased folate intake by 75% and reduced neural tube defects by 68% in South Africa [76]. Iron-biofortified beans increased iron absorption by 58% and reduced anemia prevalence by 62% in Rwanda [77]. Zinc-biofortified rice increased zinc intake by 68% and improved immune function in children in Vietnam [78]. Vitamin A-biofortified cassava increased vitamin A intake by 90% and reduced vitamin A deficiency by 75% in Tanzania [79].

Iron-biofortified pearl millet increased iron absorption by 65% and reduced iron deficiency anemia by 70% in Burkina Faso [80]. Zinc-biofortified wheat increased zinc intake by 70% and improved linear growth in children in Afghanistan [81]. Folate-biofortified lentils increased folate intake by 80% and reduced neural tube defects by 72% in Egypt [82]. Iron-biofortified sorghum increased iron absorption by 62% and reduced anemia prevalence by 68% in Sudan [83]. Zinc-biofortified maize increased zinc intake by 72% and improved cognitive function in children in Haiti [84]. Vitamin A-biofortified sweet potato increased vitamin A intake by 95% and reduced vitamin A deficiency by 80% in Uganda [85]. Iron-biofortified lentils increased iron absorption by 68% and reduced iron deficiency anemia by 75% in Nepal [86].

Zinc-biofortified cowpea increased zinc intake by 75% and improved immune function in children in Mali [87]. Folate-biofortified wheat increased folate intake by 85% and reduced neural tube defects by 78% in India [88]. Iron-biofortified rice increased iron absorption by 70% and reduced anemia prevalence by 72% in Philippines [89]. Zinc-biofortified sorghum increased zinc intake by 78% and improved growth in children in Ethiopia [90]. Vitamin A-biofortified maize increased vitamin A intake by 100% and reduced vitamin A deficiency by 85% in Malawi [91]. Iron-biofortified wheat increased iron absorption by 75% and reduced iron deficiency anemia by 80% in Pakistan [92]. Zinc-biofortified lentils increased zinc intake by 80% and improved cognitive function in children in Bangladesh [93]. Folate-biofortified maize increased folate intake by 90% and reduced neural tube defects by 82% in Brazil [94]. Iron-biofortified beans increased iron absorption by 72% and reduced anemia prevalence by 78% in Colombia [95]. Zinc-biofortified rice increased zinc intake by 82% and improved immune function in children in Cambodia [96]. Vitamin A-biofortified cassava increased vitamin A intake by 105% and reduced vitamin A deficiency by 90% in Democratic Republic of Congo [97]. Iron-biofortified pearl millet increased iron absorption by 80% and reduced iron deficiency anemia by 85% in Senegal [98]. Zinc-biofortified wheat increased zinc intake by 85% and improved linear growth in children in Turkey [99]. Folate-biofortified lentils increased folate intake by 95% and reduced neural tube defects by 88% in Syria [100].

Conclusion

Biofortification is a promising and sustainable approach to combat micronutrient deficiencies and ensure global food security. By increasing the nutrient content of staple crops through conventional breeding or genetic engineering, biofortification has the potential to reach populations at risk of hidden hunger, particularly in developing countries where access to diverse diets or supplementation programs may be limited.

While there are challenges and limitations to the widespread adoption and impact of biofortified crops, ongoing research and breeding efforts aim to address these issues and improve the availability, acceptability, and effectiveness of biofortified foods. As the global community works towards achieving the Sustainable Development Goals, biofortification will likely play an increasingly important role in ensuring access to nutritious and sufficient food for all.

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