https://openventio.us/index.php/PHOJ ISSN: 2472-3878 | Vol 11 | Issue 1 | 2026

PUBLIC HEALTH
OpenJournal

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Review Article

Biofortification and Public Health Nutrition: Agricultural Innovations for Micronutrient Deficiencys

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Article Information:
Received: 17 February 2026 | Revised: 18 March 2026 | Accepted: 15 April 2026 | Published: May 20, 2026

Cite this article:
Biju Sidharthan, Mayank Mehra, Parshuram Sial, SRIDHAR Krishnaswami (2026).Biofortification and Public Health Nutrition: Agricultural Innovations for Micronutrient Deficiencys. *Public Health Open Journal*. 11(1):444–451.
https://doi.org/10.17140/PHOJ.11.01.444

Abstract

Micronutrient deficiencies, commonly referred to as hidden hunger, remain a major global public health challenge affecting billions of people, particularly in developing countries. Deficiencies of essential vitamins and minerals such as iron, zinc, iodine, vitamin A, and folate contribute significantly to impaired immunity, anemia, stunted growth, cognitive disorders, maternal mortality, and increased susceptibility to infectious diseases. Conventional interventions including dietary supplementation and food fortification have shown positive impacts; however, limited accessibility, high implementation costs, and inconsistent coverage continue to restrict their effectiveness among vulnerable populations. Biofortification has emerged as a sustainable agricultural innovation aimed at enhancing the nutritional quality of staple food crops through conventional breeding, agronomic practices, and modern biotechnological approaches. Biofortified crops enriched with essential micronutrients provide a cost-effective and long-term strategy for combating micronutrient malnutrition while improving food security and public health outcomes. The present review critically examines the principles, approaches, health implications, and global progress of biofortification in relation to public health nutrition. The article discusses major biofortified crops, agricultural innovations, nutritional benefits, implementation challenges, and future perspectives for sustainable nutrition-sensitive agriculture. The review highlights that biofortification represents an integrated solution linking agriculture, nutrition, public health, and sustainable development for addressing hidden hunger and promoting global nutritional security.

Keywords: *Biofortification, micronutrient deficiency, hidden hunger, public health nutrition, food security, agricultural innovation, nutritional security, sustainable agriculture.*

1. Introduction

Micronutrients are essential vitamins and minerals required in relatively small quantities for maintaining normal physiological, metabolic, and immunological functions in the human body. Despite their minimal quantitative requirement, these nutrients are critically important for growth, cognitive development, reproductive health, immune defense, and overall human well-being. Deficiencies of essential micronutrients such as iron, zinc, iodine, selenium, folate, and vitamin A continue to represent one of the most widespread forms of malnutrition globally, particularly affecting populations in low- and middle-income countries. This condition, commonly referred to as "hidden hunger," occurs when individuals consume sufficient calories but fail to obtain adequate amounts of essential vitamins and minerals necessary for optimal health and development [1-2]. Micronutrient malnutrition has become a major public health concern because of its extensive impact on morbidity, mortality, productivity, and socioeconomic development. Iron deficiency remains the leading cause of nutritional anemia worldwide and is associated with fatigue, impaired cognitive performance, maternal mortality, and reduced work capacity. Zinc deficiency contributes significantly to growth retardation, weakened immunity, increased susceptibility to infectious diseases, and delayed wound healing. Vitamin A deficiency is a major cause of preventable blindness among children and substantially compromises immune function, thereby increasing vulnerability to respiratory and gastrointestinal infections. Similarly, iodine deficiency disorders affect thyroid function and neurological development, while folate deficiency contributes to neural tube defects and impaired fetal growth during pregnancy [3-5]. The burden of hidden hunger is particularly severe among vulnerable populations including infants, children, adolescents, pregnant women, lactating mothers, and economically disadvantaged communities. In many developing countries, dietary patterns are heavily dependent on staple cereal crops such as rice, wheat, maize, cassava, and millet, which often contain insufficient concentrations of bioavailable micronutrients. Limited dietary diversity, poverty, food insecurity, inadequate healthcare systems, poor sanitation, and low nutritional awareness further intensify micronutrient deficiencies. According to global nutritional assessments, billions of individuals continue to suffer from one or more micronutrient deficiencies, making hidden hunger a major obstacle to achieving sustainable public health and human development goals. In addition to its health consequences, micronutrient deficiency imposes substantial economic and social burdens on nations. Malnutrition contributes to reduced educational performance, diminished labor productivity, increased healthcare costs, and long-term economic losses [6]. Children affected by micronutrient deficiencies often experience impaired cognitive development, poor academic achievement, and reduced physical growth, ultimately affecting national human capital development. Similarly, maternal micronutrient deficiencies increase the risks of low birth weight, pregnancy complications, infant mortality, and intergenerational cycles of malnutrition. Conventional interventions for addressing micronutrient deficiencies have traditionally included dietary diversification, pharmaceutical supplementation, and industrial food fortification. Dietary diversification encourages the consumption of nutrient-rich foods such as fruits, vegetables, legumes, animal products, and fortified foods. Supplementation programs involving iron tablets, vitamin A capsules, and other micronutrient formulations have also been implemented extensively in public health systems. Likewise, food fortification strategies involving the addition of micronutrients to processed foods such as flour, salt, oil, and milk have contributed significantly to reducing nutritional deficiencies in several countries [7]. Although these interventions have demonstrated important public health benefits, they are often associated with several practical limitations. Supplementation programs require continuous financial investment, healthcare infrastructure, logistical distribution systems, and repeated administration to target populations. Food fortification approaches are generally more effective in urban populations with access to industrially processed foods but may not adequately reach rural and economically marginalized communities. Furthermore, limited healthcare access, inadequate policy implementation, poor consumer awareness, and socioeconomic disparities frequently reduce the effectiveness and sustainability of these interventions [8]. In response to these limitations, biofortification has emerged as an innovative, sustainable, and agriculture-based strategy for combating micronutrient malnutrition. Biofortification refers to the process of increasing the nutritional quality and micronutrient density of staple food crops during plant growth through conventional breeding, agronomic practices, or modern biotechnological techniques. Unlike post-harvest food fortification, biofortification enhances nutrient concentration directly within edible plant tissues, thereby enabling populations to obtain improved nutrition through routine dietary consumption of staple foods. Biofortification is increasingly recognized as a cost-effective and long-term solution for improving nutritional outcomes among vulnerable populations, particularly in rural areas where dependence on staple crops is high and access to commercial fortified foods is limited. By integrating nutritional objectives into agricultural production systems, biofortification creates an important linkage between agriculture, food systems, and public health nutrition. Biofortified crops can provide sustainable nutritional benefits without requiring major changes in dietary habits, food processing infrastructure, or repeated external interventions [9-10]. Over the past two decades, significant scientific progress has been achieved in the development and dissemination of biofortified crops enriched with iron, zinc, provitamin A carotenoids, selenium, and folate. Staple crops such as rice, wheat, maize, cassava, beans, pearl millet, lentils, and sweet potato have been successfully biofortified through both conventional breeding and advanced molecular techniques. International agricultural and nutritional research organizations have played major roles in promoting biofortification initiatives aimed at improving food and nutritional security worldwide. Advances in plant genetics, molecular biology, genomics, gene editing technologies, precision agriculture, and agronomic management have further accelerated the development of nutritionally enhanced crop varieties. Modern approaches including marker-assisted breeding, transgenic technologies, CRISPR-Cas genome editing, and soil micronutrient management are expanding the potential of biofortification programs to address multiple nutrient deficiencies simultaneously. In addition, climate-smart agricultural innovations are increasingly being integrated with biofortification strategies to improve resilience against environmental stress, declining soil fertility, and climate variability. Biofortification also contributes directly to several global sustainable development priorities, including hunger reduction, improved health, poverty alleviation, sustainable agriculture, and enhanced human productivity. Nutrition-sensitive agricultural systems incorporating biofortified crops are increasingly viewed as essential components of integrated food security and public health strategies. Furthermore, biofortification supports efforts toward achieving the Sustainable Development Goals (SDGs), particularly those related to zero hunger, good health and well-being, poverty reduction, and sustainable agricultural development [11]. Despite substantial progress, several scientific, economic, social, and policy-related challenges continue to affect the large-scale adoption and impact of biofortification programs. Factors such as limited farmer awareness, consumer acceptance, seed distribution constraints, environmental variability, post-harvest nutrient losses, and regulatory concerns may influence the success of biofortified crop implementation. Addressing these challenges requires interdisciplinary collaboration among agricultural scientists, nutritionists, policymakers, public health professionals, extension agencies, and farming communities. Therefore, the present review critically examines the role of biofortification as an agricultural innovation for addressing micronutrient deficiencies and improving public health nutrition. The article explores the major causes and consequences of hidden hunger, approaches to biofortification, health implications of biofortified crops, agricultural and technological advancements, implementation challenges, and future perspectives for achieving sustainable nutritional security and food system resilience.

2. Micronutrient Deficiency and Public Health Burden

Micronutrient deficiency, commonly known as hidden hunger, represents one of the most serious nutritional and public health challenges affecting populations across the world. Unlike protein-energy malnutrition, hidden hunger is often not immediately visible because individuals may consume adequate calories while lacking sufficient quantities of essential vitamins and minerals necessary for proper physiological functioning. Deficiencies of micronutrients such as iron, zinc, iodine, selenium, folate, and vitamin A have profound effects on human health, growth, immunity, cognitive development, reproductive health, and overall quality of life. These deficiencies are particularly prevalent in low- and middle-income countries where dietary diversity is limited and populations depend heavily on staple foods with poor micronutrient content [12].. Iron deficiency remains the most widespread micronutrient disorder globally and is considered the leading cause of nutritional anemia. Iron plays a crucial role in oxygen transport, hemoglobin synthesis, energy metabolism, and neurological function. Inadequate iron intake or poor iron bioavailability results in anemia, fatigue, reduced work productivity, impaired immune responses, and delayed cognitive development. Pregnant women and young children are especially vulnerable because of their increased physiological iron requirements. Maternal iron deficiency contributes significantly to maternal mortality, low birth weight, premature birth, and impaired fetal development. In children, iron deficiency negatively affects learning capacity, school performance, and mental development, thereby influencing long-term socioeconomic productivity. Zinc deficiency is another major global nutritional concern with important implications for immune regulation, growth, cellular metabolism,

Table 1. Major Micronutrient Deficiencies, Health Consequences, and Vulnerable Populations

Micronutrient Deficiency	Major Physiological Functions	Health Consequences	Most Vulnerable Groups	Common Dietary Sources
Iron Deficiency	Hemoglobin synthesis, oxygen transport, cognitive function	Anemia, fatigue, impaired immunity, reduced cognitive development	Pregnant women, children, adolescents	Meat, legumes, spinach, fortified cereals
Zinc Deficiency	Immune regulation, enzyme activity, growth and development	Growth retardation, weakened immunity, delayed wound healing	Infants, children, low-income populations	Whole grains, legumes, nuts, meat
Vitamin A Deficiency	Vision, immune function, epithelial integrity	Night blindness, xerophthalmia, increased infection risk	Children and pregnant women	Carrots, sweet potato, leafy vegetables
Iodine Deficiency	Thyroid hormone synthesis, neurological development	Goiter, mental impairment, developmental disorders	Pregnant women, infants	Iodized salt, seafood, dairy products
Folate Deficiency	DNA synthesis, fetal development	Neural tube defects, anemia, pregnancy complications	Pregnant women	Green leafy vegetables, legumes
Selenium Deficiency	Antioxidant defense and immune function	Cardiovascular disorders, weakened immunity	Populations in selenium-poor regions	Cereals, nuts, seafood
Calcium and Vitamin D Deficiency	Bone formation and maintenance	Osteoporosis, rickets, bone fragility	Elderly individuals and children	Milk, fish, eggs, sunlight exposure

and enzyme activity. Zinc is essential for DNA synthesis, protein metabolism, tissue repair, and normal immune responses. Deficiency of zinc weakens the immune system and increases susceptibility to diarrheal diseases, respiratory infections, and growth retardation among children. Chronic zinc deficiency may also impair reproductive health, wound healing, and neurological function. In many developing regions, cereal-based diets containing high levels of phytates reduce zinc absorption and bioavailability, thereby increasing the prevalence of zinc deficiency among vulnerable populations. Vitamin A deficiency continues to be a major cause of preventable blindness and compromised immune function worldwide. Vitamin A is essential for vision, epithelial tissue maintenance, immune responses, and cellular differentiation. Deficiency of vitamin A leads to xerophthalmia, night blindness, corneal damage, and increased susceptibility to infectious diseases such as measles and respiratory infections. Children and pregnant women are particularly at risk because inadequate vitamin A intake significantly increases morbidity and mortality associated with infectious diseases [13]. Similarly, iodine deficiency disorders affect thyroid hormone production and neurological development, leading to goiter, impaired cognitive function, developmental abnormalities, and reduced intellectual performance among children. Folate and vitamin B-complex deficiencies also contribute substantially to public health problems. Folate is particularly important during pregnancy for fetal neural tube development, DNA synthesis, and cellular growth. Deficiency may result in neural tube defects, anemia, pregnancy complications, and impaired fetal growth. Selenium deficiency affects antioxidant defense systems, immune responses, and cardiovascular health, while calcium and vitamin D deficiencies contribute to bone disorders such as osteoporosis and rickets. The burden of micronutrient malnutrition is strongly associated with poverty, food insecurity, limited dietary diversity, poor healthcare access, inadequate sanitation, and low nutritional awareness. Rural populations and economically disadvantaged communities are particularly vulnerable because they often rely heavily on staple crops such as rice, wheat, maize, cassava, and millet, which provide sufficient calories but contain relatively low concentrations of bioavailable micronutrients. Furthermore, environmental degradation, declining soil fertility, climate change, and reduced agricultural biodiversity have further affected the nutritional quality of food crops and intensified the risks of hidden hunger.

Micronutrient deficiencies also impose substantial economic and developmental consequences at national and global levels. Nutritional deficiencies reduce labor productivity, increase healthcare expenditures, impair educational attainment, and negatively affect economic growth [14]. Children affected by chronic malnutrition frequently experience stunting, reduced physical development, and cognitive impairment, thereby limiting human capital formation and long-term societal progress. Consequently, addressing micronutrient deficiencies has become a major priority for public health nutrition, sustainable agriculture, and global development initiatives.

3. Concept and Principles of Biofortification

Biofortification is an innovative agricultural and nutritional strategy aimed at increasing the concentration and bioavailability of essential micronutrients in staple food crops during plant growth and development. The primary objective of biofortification is to improve human nutritional status by developing nutrient-enriched crops capable of delivering essential vitamins and minerals through regular dietary consumption. Unlike conventional food fortification, which involves the addition of nutrients during industrial food processing, biofortification enhances nutrient levels directly within the edible portions of crops before harvest. The concept of biofortification emerged in response to the limitations associated with traditional nutritional interventions such as dietary supplementation and industrial food fortification. Although supplementation and fortification programs have contributed significantly to reducing nutritional deficiencies, their effectiveness is often limited by inadequate healthcare infrastructure, high implementation costs, inconsistent coverage, and poor accessibility among rural populations. Biofortification provides a sustainable and cost-effective alternative because it integrates nutritional improvement directly into agricultural production systems and reaches populations through commonly consumed staple foods. Biofortification is particularly valuable in developing countries where populations depend heavily on staple crops as primary dietary sources. Many staple crops naturally contain insufficient levels of bioavailable micronutrients to meet human nutritional requirements. By increasing the nutrient density of these crops, biofortification helps improve dietary quality without requiring substantial changes in food habits or consumption patterns. This makes biofortification especially suitable for low-income communities with limited access to diverse diets, nutritional supplements, or commercially fortified foods. The effectiveness of biofortification depends on several key principles. First, biofortified crops must contain significantly increased concentrations of target micronutrients capable of improving human nutritional status. Second, the nutrients present within biofortified crops must exhibit adequate bioavailability so that they can be effectively absorbed and utilized by the human body. Factors such as phytate content, food processing methods, and dietary interactions influence nutrient bioavailability and therefore must be considered during crop development [15]. Another important principle is agronomic and environmental adaptability. Biofortified crop varieties must maintain high productivity, pest resistance, climate resilience, and compatibility with local farming systems to ensure farmer acceptance and widespread cultivation. Farmers are unlikely to adopt nutritionally enhanced varieties if they compromise yield, disease resistance, or marketability. Therefore, successful biofortification programs integrate nutritional enhancement with desirable agronomic characteristics. Consumer acceptance also represents a critical factor in biofortification success. Biofortified crops should retain acceptable taste, texture, cooking quality, and appearance to ensure public acceptance and dietary adoption. For example, orange-fleshed sweet potatoes enriched with provitamin A carotenoids have been successfully introduced in several regions after awareness programs highlighting their nutritional benefits and culinary suitability. Biofortification can be achieved through several approaches including conventional plant breeding, agronomic practices, and modern biotechnological methods. Conventional breeding involves selecting naturally nutrient-rich parent lines and crossing them with high-yielding crop varieties to produce nutritionally improved offspring. Agronomic biofortification focuses on applying micronutrient fertilizers and soil management practices to enhance nutrient uptake during crop growth. Modern biotechnology and genetic engineering techniques enable direct modification of metabolic pathways responsible for nutrient accumulation within crops [16]. The major micronutrients targeted through biofortification include iron, zinc, provitamin A carotenoids, folate, selenium, and iodine. Staple crops such as rice, wheat, maize, pearl millet, cassava, sweet potato, lentils, and beans have been extensively biofortified to address region-specific nutritional deficiencies. These crops are capable of delivering improved nutritional benefits to populations through routine dietary intake. Biofortification also aligns closely with the principles of nutrition-sensitive agriculture, which emphasizes the integration of agricultural production with human nutritional outcomes. By linking crop improvement with public health objec-

Table 2. Biofortification Approaches, Target Crops, and Nutritional Benefits

Biofortification Approach	Major Technique	Target Crops	Target Nutrients	Major Advantages
Conventional Plant Breeding	Cross-breeding of nutrient-rich and high-yield varieties	Wheat, rice, beans, pearl millet	Iron, zinc, provitamin A	Cost-effective and environmentally sustainable
Agronomic Biofortification	Application of micronutrient fertilizers and soil amendments	Rice, wheat, maize	Zinc, selenium, iron	Rapid nutrient enhancement and improved crop nutrition
Genetic Engineering	Modification of nutrient biosynthesis pathways	Rice, cassava, maize	Provitamin A, iron, folate	Precise nutrient enhancement and higher efficiency
Marker-Assisted Selection	Molecular identification of nutrient-rich traits	Lentils, millet, maize	Iron and zinc	Accelerated crop improvement programs
CRISPR-Cas Gene Editing	Genome editing for targeted nutrient accumulation	Rice, wheat, banana	Multiple micronutrients	Improved precision and climate resilience
Integrated Nutrient Management	Combined use of organic and inorganic nutrient sources	Cereals and legumes	Zinc, iron, selenium	Improved soil fertility and sustainable production
Microbial-Assisted Biofortification	Use of beneficial microbes for nutrient uptake	Cereals and vegetables	Zinc and iron	Enhanced nutrient bioavailability and plant health

tives, biofortification contributes to sustainable food systems, reduced malnutrition, improved health outcomes, and enhanced socioeconomic development. Furthermore, biofortified crops support several global sustainable development priorities related to hunger reduction, health promotion, poverty alleviation, and agricultural sustainability. Recent advances in plant genomics, molecular breeding, gene editing technologies, and precision agriculture are further strengthening the potential of biofortification programs. Marker-assisted selection, CRISPR-Cas genome editing, and molecular characterization techniques are accelerating the development of crops with enhanced nutrient accumulation and improved environmental adaptability. These technological innovations are expected to expand the future scope of biofortification as an integrated strategy for combating hidden hunger and promoting global nutritional security.

4. Approaches to Biofortification

4.1 Conventional Plant Breeding

Conventional breeding is one of the most widely used approaches for developing biofortified crops. This method involves identifying naturally nutrient-rich crop varieties and crossing them with high-yielding cultivars to produce nutritionally enhanced offspring. Conventional breeding is considered cost-effective, socially acceptable, and environmentally sustainable. Several successful biofortified crops developed through conventional breeding include iron-rich beans, zinc-enriched wheat, provitamin A maize, and orange-fleshed sweet potato. Breeding programs focus on improving nutrient accumulation while maintaining crop yield, pest resistance, and environmental adaptability.

4.2 Agronomic Biofortification

Agronomic biofortification involves the application of mineral fertilizers, soil amendments, and improved agricultural practices to enhance micronutrient uptake by crops. Zinc fertilizers, selenium-enriched fertilizers, and foliar nutrient sprays are commonly used to improve crop nutritional quality. Soil health management, irrigation practices, microbial inoculation, and integrated nutrient management also contribute to increased micronutrient bioavailability in agricultural systems. Agronomic biofortification provides rapid improvements in crop nutrient content but may require continuous fertilizer application.

4.3 Genetic Engineering and Biotechnology

Modern biotechnology and genetic engineering techniques enable precise enhancement of nutrient biosynthesis pathways within crops. Transgenic approaches have facilitated the development of crops with significantly increased vitamin and mineral concentrations. One of the most notable examples is provitamin A-enriched rice, commonly known as Golden Rice, developed to address vitamin A deficiency [17]. Advances in CRISPR-Cas gene editing, molecular breeding, and genomic selection are further accelerating biofortification research and crop improvement programs. Although genetically engineered biofortified crops offer substantial nutritional potential, concerns regarding biosafety, regulatory approval, consumer acceptance, and ethical considerations continue to influence their adoption.

4.4 Major Biofortified Crops and Nutrients

Biofortification initiatives have focused primarily on staple crops widely consumed in regions affected by micronutrient deficiencies. These crops serve as important dietary sources capable of delivering essential nutrients to vulnerable populations. Iron-biofortified beans and pearl millet are widely promoted to combat anemia, particularly among women and children. Zinc-enriched rice and wheat improve immune function and growth outcomes, while provitamin A maize, cassava, and orange-fleshed sweet potato address vitamin A deficiency. Biofortified crops are increasingly being integrated into school feeding programs, public health nutrition initiatives, and agricultural extension systems to maximize nutritional impact and community acceptance.

4.5 Public Health Benefits of Biofortification

Biofortification offers substantial public health advantages through sustainable improvement of dietary micronutrient intake. Consumption of biofortified crops has been associated with improved hemoglobin levels, enhanced vitamin A status, better immune function, and reduced nutritional deficiency disorders. Unlike supplementation programs that require repeated distribution and healthcare infrastructure, biofortified crops provide continuous nutritional benefits through routine dietary consumption. Biofortification is therefore particularly effective for rural populations with limited healthcare access. The integration of biofortified crops into agricultural systems also contributes to food security, poverty reduction, maternal health improvement, child development, and long-term nutritional resilience. Furthermore, biofortification supports several global sustainable development goals related to hunger reduction, health promotion, and sustainable agriculture.

4.6 Role of Agriculture in Nutrition-Sensitive Development

Agriculture plays a central role in improving public health nutrition by influencing food availability, dietary diversity, and nutrient accessibility. Nutrition-sensitive agricultural systems prioritize not only crop productivity but also nutritional quality and human health outcomes [18-19]. Biofortification represents an important component of nutrition-sensitive agriculture because it directly links crop production with micronutrient delivery. Agricultural diversification, sustainable farming practices, home gardening, and climate-resilient crop production further contribute to improved nutritional outcomes. Collaboration among agricultural scientists, nutritionists, public health experts, policymakers, and rural communities is essential for integrating nutrition objectives into agricultural development strategies.

4.7 Challenges and Limitations of Biofortification

Despite significant progress, several challenges continue to affect large-scale implementation of biofortification programs. Limited farmer awareness, inadequate seed distribution systems, low consumer acceptance, and insufficient policy support may hinder adoption of biofortified crops. Environmental factors such as soil composition, climate variability, and crop management practices can influence nutrient accumulation and bioavailability. Additionally, post-harvest processing, cooking methods, and storage conditions may reduce nutrient retention in biofortified foods [20]. Regulatory barriers, intellectual property concerns, biosafety evaluations, and sociocultural perceptions also affect the acceptance of genetically engineered biofortified crops in certain regions. Long-term success therefore requires integrated strategies involving farmer education, public awareness campaigns, nutritional monitoring, agricultural extension services, and supportive government policies.

4.8 Recent Advances and Future Perspectives

Recent technological advances in molecular breeding, genomics, artificial intelligence, and precision agriculture are transforming biofortification research and implementation. Gene editing technologies such as CRISPR-Cas systems offer opportunities for precise nutrient enhancement without introducing foreign DNA [21-22]. Climate-smart biofortification strategies are also being developed to address the combined challenges of climate change, soil degradation, and nutritional insecurity. Future biofortification programs may increasingly focus on multiple nutrient enrichment, enhanced nutrient bioavailability, and resilience to environmental stress. Integration of biofortification with sustainable agriculture, food systems transformation, digital agriculture, and public health interventions will likely strengthen global efforts toward nutritional security and sustainable development. Continued investment in research, interdisciplinary collaboration, and international policy support will remain essential for expanding the impact of biofortification programs worldwide.

5. Conclusion

Micronutrient deficiencies continue to pose major challenges to global public health, food security, and socioeconomic development. Biofortification has emerged as an innovative, sustainable, and cost-effective agricultural strategy for improving the nutritional quality of staple food crops and combating hidden hunger among vulnerable populations. Through conventional breeding, agronomic practices, and modern biotechnology, biofortified crops enriched with iron, zinc, provitamin A, and other essential nutrients provide long-term nutritional benefits without requiring substantial changes in dietary habits. Biofortification therefore represents a critical intersection between agriculture, nutrition, and public health. Despite challenges related to adoption, regulation, awareness, and implementation, continued scientific advancement and policy support are likely to strengthen the role of biofortification in achieving sustainable nutrition-sensitive agriculture and global food security. Future agricultural systems must increasingly prioritize nutritional quality alongside crop productivity to address the growing burden of micronutrient deficiencies and ensure healthier, more resilient populations worldwide.

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