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Biofortification as a Sustainable Solution for 'Hidden Hunger': Evaluating its Impact on the Environment, Nutrition, Culture, and Ethics

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First, my success would not have been possible without the support of my family. Thank you for teaching me to find my passions and then pursue them to the best of my ability. I would also like to extend my sincere appreciation to Dr. Ahmad Fakhoury, Dr. Jason Bond, and the rest of the Plant Pathology Laboratory members for mentoring me. My undergraduate experience has been greatly enhanced by the opportunities they have provided. Finally, I would like to thank the University Honors Program for giving me the opportunity to write this thesis and for their investment in my education. I have gained valuable experience through the program that has largely impacted my education at Southern Illinois University-Carbondale.

BIOFORTIFICATION AS A SUSTAINABLE SOLUTION FOR ‘HIDDEN HUNGER’: EVALUATING ITS IMPACT ON THE ENVIRONMENT, NUTRITION, CULTURE, AND ETHICS

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Acknowledgements

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Biographical Note

Elysia Lewis is a senior at Southern Illinois University-Carbondale (SIUC) pursuing a double major in Crop, Soil, and Environmental Management and Spanish. At SIUC, she is a member of the women's soccer team, works as an undergraduate researcher in the Plant Pathology Laboratory, is a student in the Honors Program, and serves as a Transfer Transition Leader. Lewis also received a REACH grant with another undergraduate student for the 2021-2022 school year to study the characterization of endophytes with potential biocontrol activity against soilborne pathogens and their beneficial effects on plant health. After graduation, she plans to attend graduate school to study sustainable agriculture or a related field.

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Abstract

Micronutrient malnutrition, also referred to as 'hidden hunger', negatively impacts the health of millions of people around the world. Because of this, several strategies to reduce malnutrition have been proposed, one of which is biofortification. The process of biofortification increases the nutrient content of plants during their vegetative life cycle. Research has been conducted that shows the ability of biofortification to increase micronutrient content in crops, so the next step is successful implementation and adoption by consumers. This paper reviews several publications that look at biofortification with respect to the environment, sustainability, human nutrition, culture, and ethics from a variety of places around the world. The ultimate goal is to determine if biofortification provides a sustainable solution to combat micronutrient deficiency. There are clear benefits of biofortification that demonstrate its potential for success, but there are still many barriers to be overcome for its successful application.

Introduction

Background

As the world prepares to feed the projected 9.6 billion people by the year 2050, new strategies to produce crops efficiently are being considered, yet the fight against hidden hunger is still one of the leading concerns worldwide. Hidden hunger is micronutrient deficiency caused by insufficient vitamins and minerals in a diet, and it leads to several serious illnesses including intellectual disabilities, stunted growth, premature death, and increased risk of developing chronic diseases (ex: cardiovascular diseases and cancers) (Jha & Warkentin, 2020). It affects one in three people worldwide (Bouis et al., 2013). The three most common deficiencies around the world are vitamin A, iron, and zinc. It is a major public health concern in parts of the world such as Sub-Saharan Africa, the Caribbean, and East and West Asia (Siwela et al., 2020). Because micronutrient malnutrition causes significant health problems now and in the foreseeable future, greater emphasis is being put on finding a solution.

Fortification Strategies

Different fortification strategies are being used to address hidden hunger. The two main approaches being studied are direct intervention and indirect intervention. Direct intervention is nutrition-specific and concentrates on food consumption behavior such as food supplementation and creating a diverse diet. Indirect intervention is nutrition-sensitive, and it includes biofortification (de Valença et al., 2017). There are different factors that determine which is the most appropriate strategy for a specific location, such as the prevalence of certain deficiencies, available food sources, infrastructure, and government regulation (Olson et al., 2021). The rural poor population is disproportionately affected by micronutrient malnutrition, and direct intervention strategies are not readily available (Bouis et al., 2013). Therefore, indirect fortification (i.e., biofortification) seems to be the best solution currently.

Methods of Biofortification

Biofortification is the process in which the amount or availability of essential nutrients in crops is increased during plant growth (de Valença et al., 2017). It differs from other fortification strategies because it targets the crop directly instead of adding supplements during food processing (Malik & Maqbool, 2020). There are three main methods used in biofortification: conventional plant breeding, soil and foliar fertilizer application, and genetic engineering (Garcia-Casal et al., 2016). The fundamental goal of biofortification is to improve the nutritional quality of crops with already favorable agronomic traits (Singh et al., 2016) while maintaining both the agricultural requirements of the farmer (i.e., yield) and cultural acceptability (i.e., color, taste, and cooking time) (HarvestPlus, n.d.). The product then must be physically and economically available to the consumer while retaining its nutritional quality during preparation (Siwela et al., 2020). Only when all these criteria are met is the biofortification process successful. The process is highly collaborative, and it involves agriculturalists, nutritionists, economists, and public health experts (HarvestPlus, n.d.). Because biofortification targets highly malnourished communities while involving many groups of people, it provides a better sustainable option to fight hidden hunger.

Biofortification has reduced micronutrient deficiency in populations around the world (Hummel et al., 2018). Traditionally, staple crops (i.e, corn, rice, beans, cassava, millet, and potatoes) have been the major target for biofortification because they are consumed in large quantities by people in malnourished populations, but they lack a high micronutrient content (Talsma et al., 2017). Because of this, biofortification of pulse crops is being studied. Pulse crops are common in the traditional diets of different cultures, and they are rich in protein, vitamins, and minerals. Pulse crops include lentils, mungbeans, chickpeas, common beans, and peas (Jha & Warkentin, 2020). After its success in staple crops, scientists realized the need to use different biofortification methods to expand its benefits to common, traditional foods as well.

Conventional plant breeding in biofortification is achieved through different mechanisms. Parent lines with a high concentration of the desired micronutrient can be crossed with each other to cultivate advanced offspring rich in micronutrients (Siwela et al., 2020), or parent lines with reduced levels of anti-nutrients—plant compounds that reduce nutrient absorption in the human body—can be crossed to increase bioavailability (Campos-Bowers & Wittenmyer, 2007). Bioavailability is the amount of a nutrient that can be used in physiological functions (Siwela et al., 2020). This method of biofortification helps small holder farmers improve micronutrient density in their crops (HarvestPlus, n.d.), and it is a long-term sustainable approach to combatting health concerns in low-income areas (Jha & Warkentin, 2020). There are, however, certain challenges associated with plant breeding for biofortification. First, conventional breeding is time consuming because breeders must first identify the right trait and then breed it into the crop (Siwela et al., 2020). Once the gene is in the crop, issues such as low heritability and linkage drag can arise (Malik & Maqbool, 2020) or uncontrolled gene interactions can reduce plant vigor (Garcia-Casal et al.,

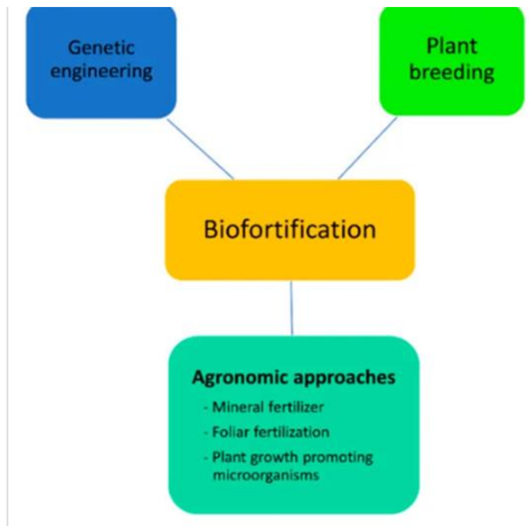


Figure 1. Different approaches of biofortification for improvement of nutritional profile.

Reproduced from Jha & Warkentin, 2020

2016). There have been successes using conventional breeding for certain micronutrients such as vitamin A and zinc, but these challenges must be overcome for more widespread integration.

A second biofortification method is soil and foliar micronutrient applications. Plant available minerals in the soil are sometimes depleted and, therefore, are unavailable for translocation into the plant. Mineral fertilizers—inorganic compounds that contain micronutrients—can be applied to the soil which then increase the amount of minerals transferred to the edible portions of the plant (Jha & Warkentin, 2020). Foliar fertilization is when fertilizers are sprayed onto the above ground plant tissues to supply plant nutrients. Foliar applications can supply small amounts of both micronutrients and macronutrients without causing harm to the plant (Alshaal & El-Ramady, 2017). The efficacy of soil and foliar applications is determined by many environmental factors including temperature, humidity, wind speed, and time of application as well as plant tissue permeability. Warm, moist conditions increase tissue permeability which is important in the absorption of the mineral fertilizer (Alshaal & El-Ramady, 2017). Soil and foliar applications are beneficial when immediate crop response is necessary, nutrient loss needs to be controlled, application of immobile plant nutrients such as iron and zinc is needed, and when administration of other fertilizers is already occurring which reduces application costs (Alshaal & El-Ramady, 2017). While studying soil and foliar micronutrient applications, scientists identified certain limitations. First, regular or continuous application of fertilizers is occasionally necessary. This can cause adverse side effects to soil health or the availability of other soil minerals. Additionally, geographic region determines the soil composition and therefore its soil micronutrient deficiencies. Because these are not the same everywhere, certain fertilizers may not be adequate for all locations. Finally, outside factors, such as weather conditions, can limit the effectiveness of the plant amendments which not only reduces mineral bioavailability but also makes it cost-prohibitive (Garcia-Casal et al., 2016). Many of these barriers can be overcome with adequate research of the specific location. Better understanding of environmental features will boost the success of this type of biofortification.

The third approach to biofortification is genetic engineering, and it is the most recent advancement. Genetic engineering uses genes from other sources without taxonomic limitations and introduces them directly into the crop (Singh et al., 2016). Genetic engineering is most often used in biofortification when the desired micronutrient does not exist naturally or in sufficient quantity in the crop, conventional breeding cannot produce the appropriate outcome, or the crop's antinutrients inhibit micronutrient uptake. It became a viable option in recent years due to progressions in genome sequencing (Jha & Warkentin, 2020). Crops that have undergone genetic engineering have the capability of accumulating large amounts of vitamins and minerals in the edible portions which would benefit consumers (Campos-Bowers & Wittenmyer, 2007). It has so far been successful in crops including wheat, rice, corn, and soybeans (Jha & Warkentin, 2020). There are currently cultural, ethical, and scientific barriers to the success of genetic engineering in biofortification. Culturally, using transgenes is expensive and time consuming which makes it unavailable to many people especially where access to infrastructure and technology is limited (Siwela et al., 2020). Scientifically, greater understanding of crop genomes and endogenous metabolic pathways is needed for improved crop response. Ethical concerns have also been raised regarding food safety and labeling of genetically modified crops, intellectual property rights, and genetic resource conservation (Garcia-Casal et al., 2016). Genetic engineering has the potential to decrease micronutrient malnutrition as long as it addresses current social and ethical concerns.

Benefits of Biofortification

There are many benefits of biofortification. First, biofortification is directed at populations in remote locations where access to fortified foods is limited (Olson et al., 2021). Where other strategies target populous areas in the hopes that the surpluses make it to rural communities, biofortification is unique in that it targets rural areas with the intention of the surpluses spreading to urban communities. This distinction is important because rural areas see the greatest micronutrient deficiencies. Biofortification can be used to increase several nutrients including iron, iodine, zinc, calcium, and selenium as well as vitamins such as vitamins A, B, C, and E (Alshaal & El-Ramady, 2017). This is important because many heavily consumed crops in several cultures lack essential nutrients. Therefore, the ability to successfully biofortify crops with an array of vitamins and minerals allows the crops to grow in nutritional value.

Reproduced from Siwela et al., 2020

Furthermore, genetic engineering can support the introduction of more than one micronutrient in the same crop which is higher in nutritional quality and more beneficial economically (Olson et al., 2021). By the end of 2016, more than 20 million people in 30 countries were eating biofortified crops, and 150 varieties within 10 crops were available (Jha & Warkentin, 2020). Developments in biofortification continue to be made with the hopes of reducing or eliminating malnutrition caused by micronutrient deficiency.

Drawbacks of Biofortification

Although there are clearly many advantages to biofortification, there are still some drawbacks. For example, biofortification cannot provide the same amount of micronutrient that industrially fortified foods or food supplements can; however, rural populations do not have easy access to these supplements (Singh et al., 2016). This does not detract from the improvements biofortification has contributed; however, nutrient levels need to be increased if biofortification is going to completely irradicate micronutrient deficiencies on its own. The issue of malnutrition is often considered only in terms of health. Another potential drawback is that although the United States Department of Agriculture has a technical definition of biofortification, there is currently no legal definition. Therefore, potential benefits and drawbacks need to be carefully communicated to the public (Lockyer et al., 2018). Presently, biofortification is only concentrated on a few staple crops, so there is a growing concern that communities will become reliant on a small number of crops. This reduces both environmental and diet diversity (Johns & Eyzaguirre, 2007). Diet diversity is important because there are nutrients found in other foods that are not included in the biofortified staple crops. This is also why current biofortification strategies tend to fail in the long run because they do not consider the implications of "regular" food on micronutrient deficiencies (Korthals, 2011).

Statement of Purpose

Biofortification demonstrates strong potential to be used as a sustainable solution to fight hidden hunger due to its environmental and nutritional benefits; however, strong considerations need to be made towards its impact on culture and ethics if sufficient acceptance and adoption is to be expected.

Environment

Background

While the focus of biofortification is to provide a solution for micronutrient malnutrition, there are other factors that need to be understood. One major factor is the effect of biofortification on the environment. If environmental health is sacrificed for improved nutritional quality, the solution will not be sustainable. The availability of micronutrients in crops and their positive economic and ecological impact is enriched by efficient management practices (Malik & Maqbool, 2020); however, half of the land available for farming is low in at least one micronutrient (Campos-Bowers & Wittenmyer, 2007). For example, zinc and iron deficiency is common in South African soils. Zinc deficiency causes stunted growth, chlorosis, reduced leaf size, and low crop quality in plants while also contributing to zinc deficiency among the people of South Africa (Siwela et al., 2020). Current research, therefore, highlights the importance of good land management strategies.

There are many factors that influence a plant's ability to utilize nutrients from the soil including soil pH, aeration, temperature, texture, organic matter content, moisture, nutrient interactions, and farming standards (Malik & Maqbool, 2020). Therefore, successful implementation of biofortification must not only increase the number of micronutrients the crop can produce but also interact with soil conditions in a way that allows the crop to efficiently use the nutrients. A sufficient quantity of macronutrients (i.e., nitrogen, potassium, and phosphorus) and micronutrients increases their transportation from the soil into the edible portions of the crop as well as promotes strong root architecture (Khan et al., 2019). There is a strong correlation between macro- and micronutrient content and biofortification efficiency. For example, studies conducted with wheat found that increased nitrogen fertilization elevated zinc and iron concentrations in the grain (de Valença et al., 2017). Crop breeders continue to develop varieties suited for different environmental conditions. This allows elite germplasms to be bred with increased micronutrient content while already adapted to diverse climate conditions (HarvestPlus, n.d.). Agronomic biofortification is being studied to withstand negative environmental changes through fertilizer applications and foliar sprays (Siwela et al., 2020) which suggest biofortification as a potential solution for current land management strategies as well.

Soil Amendments

The two main approaches of biofortification from agronomic management are soil amendments and foliar application. Soil amendments apply micronutrients directly to the soil. This increases the micronutrient content available for plant uptake. If applied correctly, micronutrient applications pose little to no environmental threat because they bind strongly in the soil therefore making nutrient leaching an insignificant concern. On the other hand, special care needs to be taken when timing fertilizer applications because repeated application of micronutrients can cause build up over time initiating nutrient toxicity in the plant. Nevertheless, if supply and demand in the plant is equal, this is not an issue (de Valença et al., 2017). An alternative strategy to chemical soil fertilizers has been proposed to combat these issues: biofertilizers. Biofertilizers consist of biological organisms which have no chemical or synthetic components. They typically consist of beneficial soil microorganisms, such as rhizobia and mycorrhizal fungi, and plant growth promoting microorganisms, such as Bacillus, Pseudomonas, and Enterobacter (Jha & Warkentin, 2020). These increase plant growth, produce antifungal metabolites and antibiotics, activate plant-disease resistance, and dissolve insoluble nutrients.

They are an environmentally friendly way to promote soil health and increase nutrient content while simultaneously alleviating the concern of nutrient build-up. To date, studies have shown that biofertilizers have promoted plant growth and nutrient status as well as reduced disease presence and increased yield (Khan et al., 2019). Plant growth-promoting microorganisms also boost the bioavailability of nutrients in the soil. They have been shown to increase the availability of iron, selenium, and zinc in legume crops (Jha & Warkentin, 2020). Biofertilizers have been suggested as a way to mitigate detrimental environmental effects caused by chemical fertilization as well as field productivity (Khan et al., 2019). Micronutrient applications applied as soil amendments or biofertilizers could realistically improve poor land quality common in certain parts of the world while also fixing nutrition status.

Foliar Applications

Foliar fertilizers are applied directly to the vegetative parts of the plant (i.e., stems and leaves). This method is usually more effective for nutrient uptake, especially for leafy vegetable and cereal crops, because nutrient immobilization in the soil is negated, and nutrient availability for the edible plant portions is more productive. Nevertheless, foliar application is more expensive and requires greater expertise not to mention environmental conditions, such as rain, can impede this method (de Valença et al., 2017). According to a study reviewed in "Agronomic biofortification of crops to fight hidden hunger in sub-Saharan Africa", increased iron content in crops was most effective

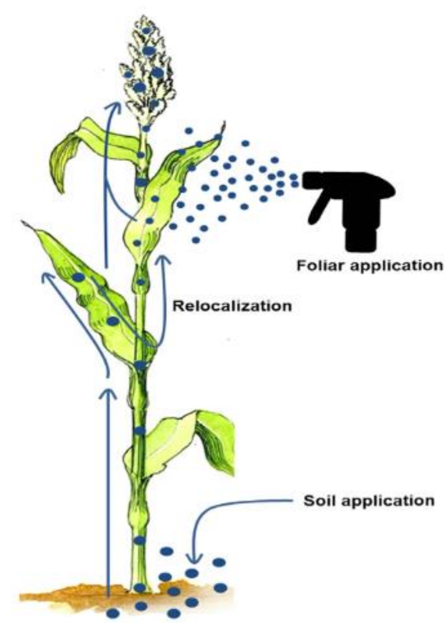


Fig. 1. Agronomic biofortification is the application of micronutrient-containing mineral fertilizer (blue circles) to the soil and/or plant leaves (foliar), to increase micronutrient contents of the edible part of food crops. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Reproduced from de Valença et al., 2017

through foliar application of iron. Additionally, foliar application of zinc increased wheat grain zinc concentration by 84% (de Valença et al., 2017). This implies that foliar application is effective in biofortification efforts.

Pros and Cons of Biofortification on the Environment

Biofortification practices improve both environmental factors as well as field productivity which is important to growers. Biofortified plants have been shown to revitalize depleted soils which simultaneously increases the crop's nutritional quality (Campos-Bowers & Wittenmyer, 2007). Additionally, research endeavors have found that biofortified seeds have higher yield, reduced susceptibility to stress, and increased survival (Singh et al., 2016). These findings are important to growers because they promote economic profitability not only through yield increases but also reduce the need for herbicide applications. Because less herbicides would need to be applied, it is also more environmentally friendly. On the other hand, there are some environmental concerns related to the implementation of biofortification such as decreased biodiversity, pollution, and water use. Maintaining biodiversity is crucial in agronomic practices, therefore sufficient research needs to be done to study the interaction between biofortified crops and their actual impact on biodiversity. However, biofortified varieties are lines with increased micronutrient content crossed with locally adapted lines which helps maintain a level of biodiversity (Garcia-Casal et al., 2016). Also, the relationship between production, transportation, and storage of vitamins and minerals in plants is a highly complex process. There are concerns that increasing the level of micronutrients in the crop could negatively impact these processes and consequently the plant itself (Campos-Bowers & Wittenmyer, 2007). Finally, the different environmental conditions can have an impact on the genotype. It cannot be assumed that a variety will perform the same way in every setting (Hummel et al., 2018). These changes are important to know especially when it comes to adequate nutrient content or consumer acceptance traits such as flavor and texture. These will need to be studied in greater detail in order to elimante potential consumer resistance they cause. Future research will compare current local crop varieties and biofortified lines to evaluate their productivity, impact on soil and climate conditions, and nutritional quality (HarvestPlus, n.d.). It is assumed that the biofortified varieties will perform better than current varieties. With better understanding of the effect biofortification has on the environment, the more likely the varieties are to be produced for specific areas.

Sustainability

Introduction

Biofortification has proven benefits for combatting micronutrient malnutrition; however, if it is not sustainable, it will not justify the resources it takes to implement. The United Nations defines sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, n.d.). The sustainability of biofortification includes many components such as agriculture, environment, economy, and culture. The food systems that are currently used in developing countries, where malnutrition is most severe, are highly involved. Successful food systems provide all of the components necessary to sustainably provide for its population, but the complexities of certain food systems cause an inadequate supply for its people (Bouis & Welch, 2010). The Copenhagen Consensus has continuously stated that applying micronutrients is one of the most cost-effective solutions in development that has proven results. A few strong examples are iodized salt folic acid fortified wheat and iron fortified maize. Iodizing salt costs approximately 0.05 US dollars per person, and fortifying wheat and maize costs about 0.12 US dollars per person each year. This amounts to fifteen US dollars per person in their lifetime with a return of twenty-six US dollars in health care savings and productivity. For every dollar spent on fortification, the economy earns nine dollars in the return on investments (Olson et al., 2021). This example provides compelling evidence in the argument that biofortification can be economically beneficial and sustainable over time. There have been several proposed solutions to malnutrition which have failed due to socioeconomic, infrastructure, and political limitations in developing countries (Singh et al., 2016). Currently, some of the most prevalent barriers to sustainable application of micronutrients include changing demographics, lack of resources, climate change, and diet variation (Lockyer et al., 2018). Sustainable solutions to micronutrient malnutrition will only be possible by creating solutions that combine agriculture, nutrition, health, and policy (Bouis & Welch, 2010). Biofortification emphasizes not only agricultural and environmental sustainability, but also sustainable policies and interventions so that it survives as a long-term solution.

Process Sustainability

Solutions to overcome micronutrient malnutrition have been a challenge to achieve because a majority of the most severely malnourished people live in rural settings where access to commercially fortified foods is limited, or price of supplements is a barrier. However, biofortification has the potential to be a sustainable solution for people in this setting. The Consultative Group on International Agricultural Research (CGIAR) proposes that dietary diversification is the most sustainable solution to combat micronutrient deficiency in urban settings where resources are more abundant whereas biofortification is the most sustainable in rural areas (de Valença et al., 2017). Biofortification is recognized as a sustainable solution for several reasons. First, both genetic and agronomic biofortification are cost-effective and can be used as a counterpart to other strategies as well (Bouis & Welch, 2010). Biofortification is considered relatively inexpensive because, after the initial investment costs, there are no additional costs to fortify the food since the micronutrients are produced directly by the crop (Malik & Maqbool, 2020). After this, biofortified seeds can be used in subsequent growing seasons, so no additional cost is required which makes it a financially sustainable solution (Singh et al., 2016). Additionally, biofortification is considered nutritionally sustainable. Because genetic biofortification produces seeds that can be planted year after year, the nutritional status of the plant can be reproduced each growing season. Additionally, the crops' germplasms (living genetic resources maintained for the purpose of breeding) are available all over the world (Jha & Warkentin, 2020). Therefore, biofortification will help reduce the prevalence of micronutrient malnutrition while simultaneously conserving nutritional quality (Singh et al., 2016). Lastly, biofortification is considered environmentally sustainable. While other strategies involve high levels of inputs (usually chemical), biofortification through plant breeding and biotechnological techniques improves the crop's nutritional status while limiting or completely avoiding field additions (Singh et al., 2016), and it is considered the most sustainable approach to combat hidden hunger on a global scale (Malik & Maqbool, 2020). All current evidence indicates that the process of biofortification is sustainable and the best option in rural areas.

Soil Sustainability

Although genetic biofortification is considered more sustainable than agronomic biofortification, agronomic biofortification still has many positive attributes. Different strategies, such as soil amendments, green manures, and plant growth promoting microorganisms, have been studied as promising approaches. Soil amendments with various micronutrients can improve both field productivity and crop quality. Also, these mineral fertilizers can be mixed with organic fertilizers which promotes soil organic matter (an important soil health quality). Increased organic matter content also provides additional beneficial qualities such as preventing erosion and increased water-holding capacity. In a study described by de Valença et. al., adding organic matter to the soil over a period of time increased soil zinc content in its plant available form.

Bioavailability of micronutrients can increase with the addition of green manures. Green manures are cover crops that are used as soil amendments. In another study highlighted by de Valença et al. demonstrated that mineral zinc application combined with green manures enhanced both zinc quantity and yield of basmati rice in India (de Valença et al., 2017). Applications of plant growth promoting microorganisms and biocontrol agents can also be used in place of pesticides. They are more environmentally sustainable due to their shorter lifespan in the soil and less synthetic components. This is important because it reduces the amount of chemicals used, and they are a less expensive solution to increase nutritional crop quality (Khan et al., 2019). Using agronomic approaches may be a key component to alleviate hidden hunger while being economically and environmentally sustainable for future populations.

Business/Market Sustainability

After the initial set up of biofortification, one of the biggest barriers to success is creating a sustainable business model that allows for it to persist. Solutions are only sustainable if each sector agrees on the model, so many biofortification efforts are emphasizing collaboration between the agriculture, government, and business sectors. First, understanding the food chain from the field all the way until it reaches a consumer’s plate is vital for creating lasting value chains. To do this, both biofortified crops and ingredients need to be prevalent and widely adopted in the global food system. Additionally, involving stakeholders will help connect people from each sector so that they can agree upon common goals and work out any impediments. Some of the current concerns that are hindering market sustainability include affordability of nutritious food, consumer demand, business education, inadequate policies, and lack of partnerships (Lockyer et al., 2018). These partnerships are especially important for rural farmers who rely on crop productivity and sales to survive. If the biofortified crops are either not producing efficiently or are not being widely adopted by consumers, growers will not be willing to grow them. Finally, creating sustainable supply chains will be required to distribute biofortified seed (Bouis & Welch, 2010). In rural settings, this can be difficult, but it is imperative that farmers receive the correct seed if they are expected to be planted. However, once these partnerships are created and initial issues are worked out, biofortification could remain sustainable even if funding decreased because the benefits of production and consumption of biofortified crops would persist (Bouis & Welch, 2010). Market sustainability is not often considered when thinking about sustainability, yet without it, successful implementation of biofortification will not exist.

Overall, understanding the sustainability of biofortification is an important aspect when considering its implementation. There is sufficient research to suggest that biofortification is economically and environmentally sustainable; however, greater emphasis needs to be put on making it sustainable in terms of business so that it can be properly set up and carried out in a way that it would benefit both producers and consumers that are greatest in need.

Nutrition

Introduction

Likely the biggest consideration throughout the process of biofortifying food crops is its effect on nutrition. Because micronutrient malnutrition has such a deleterious impact on human health, a large emphasis is put on how biofortification can improve the problem. Many people suffering from hidden hunger have an adequate number of calories in their daily food intake; however they are deficient in minerals such as iron, zinc, calcium, magnesium, copper, selenium, and iodine (Singh et al., 2016). Other common vitamin deficiencies include vitamins A, B, C, and E. Micronutrient malnutrition affects more than two billion people around the world accounting for five million child deaths each year (Bouis & Welch, 2010). The use of agronomic biofortification has seen success in different locations around the world with a number of different micronutrients. Nevertheless, its success is dependent on factors such as nutrient bioavailability in the soil, nutrient allocation in the plant, nutrient transport into the edible portion of the plant, nutrient bioavailability in the prepared food, and they physiological state of the human (de Valença et al., 2017). Throughout this section, a greater understanding of different micronutrients, what health problems are caused by micronutrient deficiencies, and the impact of nutrient bioavailability, the environment, breeding strategies, post-harvest and food preparation, and potential drawbacks of biofortification on nutrition will be gained.

Micronutrients

Micronutrients play an integral role in a human's diet and their nutrition. Micronutrients—vitamins and minerals—are just as important as macronutrients in terms of their impact on quality nutrition. They are just needed in smaller quantities in the diet (Centers for Disease Control and Prevention, 2021). According to the World Health Organization, about 30% of the world's population has at least one form of malnutrition, and approximately 3.5-5 billion people suffer from iron-deficiency while 140-250 million people are vitamin A deficient (Campos-Bowers & Wittenmyer, 2007). Micronutrients hold several roles in the human body such as contributing to mental and physical development and regulation of vital functions and metabolic processes (Malik & Maqbool, 2020). Each vitamin and mineral has its own role in the human body. First, Vitamin A plays a key role in immune function, vision, cell growth, and reproduction. Vitamin B has eight distinct forms which function in several metabolic processes including protein synthesis and carbohydrate metabolism. Vitamin C helps to support the immune system, metabolism, and synthesis of cholesterol, amino acids, and collagen. Vitamin E works as an antioxidant and aids in lipid membrane integrity, vision, and disease prevention. Some of the most common mineral deficiencies include iron, zinc, and iodine. Iron plays a key role in the blood as it partially makes up hemoglobin. It helps carry oxygen from the lungs to other parts of the body. Zinc helps with cell growth and division as well as immune functioning. Lastly, iodine plays a huge role in the synthesis of thyroid hormones which help regulate metabolism (Malik & Maqbool, 2020). Because each micronutrient plays a different role in the body, it is important to understand what each individual or population is deficient in to help create the proper biofortification strategy. As the micronutrient content increases in food crops, improved human health is expected to follow those who consume the biofortified foods.

Total population at risk of major micronutrient deficiencies and top five staple crops, by region [23].

	Asia	**Africa**	**Latin America and the Caribbean**	**Total Cases of Deficiency/Inadequate Intake**
Total population at risk				2,466,226,780
All	1,722,763,911	541,818,522	201,644,347	994,556,079
Iron	699,198,517	237,395,434	57,962,128	1,273,705,384
Zinc	901,336,413	236,801,679	135,567,293	197,965,317
Vitamin A	122,228,982	67,621,409	8,114,927	197,965,137

Reproduced from Siwela et al., 2020

Micronutrient Deficiency-Related Health Problems

	Pregnancy	Lactating mother	6–23 mo	2–5 years	5–18 years	WRA (15–49 years)	Adult men	Elderly
Micro-nutrient need	very high	very high	very high	high	moderate to high	moderate to high	low to moderate	moderate to high
Amount of food eaten	moderate	moderate	low	low, increasing with age	increases with age	moderate	high	moderate
Potential to benefit	high	high	low	low, increasing with age	increases with age	high	high	high
Potential to fully meet need	low	low	no	low, increasing with age	increases with age	high	high	high

Reproduced from Olson et al., 2021

When micronutrients are deficient in the diet, different health consequences result which are especially problematic in women and children. Micronutrient deficiencies are risky in children because they are at their prime developmental age, and they are risky in women due to their reproductive functions. Consequences of malnutrition can be outwardly inconspicuous, so it is not always apparent that someone is suffering. Negative health effects can be both physical and cognitive such as decreased immune function, stunted growth, greater susceptibility for infections, and higher risk for developing diseases such as diabetes, cardiovascular disease, and obesity (Siwela et al., 2020). There has been a growing concern for vitamin A deficiency in recent years. Because vitamin A plays a key role in vision, vitamin A deficiency is the leading cause of preventable night blindness. Also, iron deficiency is the main cause of iron-deficient anemia and childhood death. Lastly, zinc deficiency is connected to reduced immunity and childhood diarrhea (Siwela et al., 2020). Micronutrient deficiencies have a large impact on the overall health and natural functioning of the human body. This warrants greater emphasis on micronutrient malnutrition solutions such as biofortification. Biofortification could help increase micronutrients in the human diet which would reduce the presence of malnutrition and its related health problems.

Environmental Factors

The environment plays another important role in the micronutrient quality of crops. This is another reason why environmental health, especially soil health, is a priority when considering biofortification. Many micronutrients are found in the soil. If micronutrients in the soil are deficient, crop productivity is restricted which then affects the crop quality and later the nutritional value for humans. For example, in sub-Saharan Africa, 75% of the total land usable for agriculture has severe soil fertility issues due to insufficient amounts of micronutrients. This causes reduced crop productivity, lower crop nutritional quality, and high rates of malnutrition (de Valença et al., 2017). While deficiencies in the soil cause negative impacts on micronutrient availability for the crops, soil amendments provide a way to increase these levels. For example, enriching current fertilizers with zinc has been shown to increase the amount of zinc absorbed in the diet by 5%. This is expected to reduce the zinc-deficiency related disability adjusted life years by 15% (de Valença et al., 2017). Although this has already been studied for zinc, other micronutrient additions to fertilizers could also raise the micronutrient abundancy in the edible plant parts. The environment plays a role in the nutritional quality of crops, so maintaining its health is a key component of the biofortification process.

Breeding for Increased Micronutrient Content

Plant breeding is one of the three main techniques of biofortification used to increase the nutrient content in crops, therefore, it is necessary to understanding its importance. According to "Agronomic biofortification of crops to fight hidden hunger in sub-Saharan Africa", breeding crop varieties that can transfer micronutrients to the edible portion of the plant is the predominant method used (de Valença et al., 2017). This is important because even if the nutrient quantity is increased in a crop, if it is not in the edible portion, it does not benefit human nutrition. Studies under controlled conditions have shown that when crops are bred for increased nutrient content, the micronutrients are both bioavailable and absorbed in high enough quantity to improve the micronutrient status in human health (Bouis et al., 2013). A second approach of plant breeding during biofortification is breeding varieties with decreased levels of antinutrients. Antinutrients, such as phytates, tannins, polyphenolics, and oxalic acid, limit humans' ability to absorb nutrients such as calcium, iron, and zinc (Singh et al., 2016). If breeders are using this approach, they should do so with caution because antinutrients are important plant metabolites. This means that they aid in biotic and abiotic stress resistance and plant metabolism (Siwela et al., 2020). Therefore, breeding for decreased antinutrients could have a negative impact on the crop if it is not done carefully. Continued improvements in plant breeding will increase the impact of biofortification on nutrition and ultimately human health.

Bioavailability

Nutrient bioavailability determines how readily it will be absorbed into the body which, therefore, has a great impact on human nutrition. With the biofortification process, guaranteeing that the micronutrients are bioavailable is a necessary step. Bioavailability is influenced by agronomic factors, food content factors, and consumer health factors. In terms of the agronomic factors, bioavailability is influenced by the crop variety and the food processing method. The food content factors include the quantity and chemical form of the micronutrient consumed, nutrient interactions, gastrointestinal absorption (the main driver of iron and zinc bioavailability), and the structure of the dietary matrix. The human health factors that influence bioavailability include the consumer's age, sex, nutrient status, ethnicity, and physiological state (de Valença et al., 2017). Understanding how all these factors positively or negatively impact bioavailability helps biofortification strategies benefit the greatest number of people. When researching nutrient bioavailability, it is usually better to study humans with current deficiency issues to measure their response. This is due to changes in absorption rates depending on nutrient status in the body. For example, when studying iron bioavailability, people with sufficient iron in their body absorb about 3-5% of iron from their food sources whereas people deficient in iron absorb about two times as much from their food sources (King, 2002). Zinc absorption also increase when people have deficiencies in those micronutrients (de Valença et al., 2017). Ensuring high levels of bioavailability in the crop increases the efficacy of biofortification.

Post-Harvest/Food Preparation

The final step in biofortification as it relates to nutrition is the impact that post-harvest methods and food preparation have on micronutrient content. Depending on the way crops are harvested or cooked, micronutrients can be lost, so using methods that reduce this loss is critical. For example, germination, fermentation, and soaking cereal grains before cooking increases zinc and iron bioavailability (King, 2002). Additionally, during bread production and grain milling, iron, manganese, selenium, and copper are rarely lost, and parboiling rice with added micronutrients increases nutrient content in the grain (de Valença et al., 2017). A second example references the orange-fleshed sweet potato (OFSP). According to the HarvestPlus Program, plant breeders should breed OFSP with a beta-carotene level of 3200 μg/100g OFSP (Hummel et al., 2018). One study showed that 90% of beta-carotene was retained by South African children in a mashed and boiled form. Also, 77% of beta-carotene was retained when OFSP was steamed for 30 minutes, and 78% was retained both when it was deep-fried for ten minutes and when it was boiled in water for twenty minutes (Siwela et al., 2020). Another important factor when addressing post-harvest and food preparation is educating growers and consumers on the best way to preserve bioavailability. For the increased nutritional quality of crops to be able to positively impact human nutrition, the crops need to be both harvested and prepared in a way that conserves the nutrients all the way through consumption.

Potential Disadvantages Related to Nutrition

While there are many advantages to biofortifying crops for increased nutritional quality, there are also some drawbacks. For one, biofortification efforts have been focused more on starchy staple crops. Therefore, there is concern that biofortification would create dependence on these high calorie staples rather than traditional diets. This also leads to increased fear of reduced biodiversity as some other crops may become less important or under consumed (Johns & Eyzaguirre, 2007). A second potential disadvantage is the interaction between the increased nutrient levels and other micronutrients or microorganisms in the body. Some micronutrient interactions decrease each other's bioavailability. Another study found that patients suffering from malaria became sicker with increased iron levels because iron stimulates malaria microorganisms (Korthals, 2011). This shows how additional nutrients can negatively interact with current body functions. Health officials should know how different nutrients react with common microorganisms found in the body. Lastly, because many staple crops are used in the production of different snacks and food products, there is some apprehension that biofortified crops will be used to make foods high in fat, sugar, or salt (Talsma et al., 2017). All of these disadvantages can be avoided through proper understanding of different consumer food systems and their needs.

Culture

Introduction

Food plays a critical role in culture. Food systems, crops, and recipes are used generation after generation. Therefore, when studying biofortification, it is imperative that its impact on culture is a major research objective. If it does not fit consumer wants, it is highly unlikely that it will be adopted regardless of its health or environmental benefits. According to Johns and Eyzaguirre, "human food choices are determined by cultural values, economic factors, organoleptic and esthetic preference for foods and for dietary variety. Because dietary behavior and choices are directed towards foods, not nutrients, nutrient content alone is unlikely to be sufficient reason to expect their acceptance" (Johns & Eyzaguirre, 2007). This statement captures the main struggle that biofortification faces for cultural adoption. In order to overcome this problem, researchers need to focus on developing varieties that are not only nutritionally better but also have attractive characteristics including taste, texture, and color (HarvestPlus, n.d.). To understand the impact of biofortification on culture, it is necessary to understand its implication on both growers and consumers as well as the value of community education.

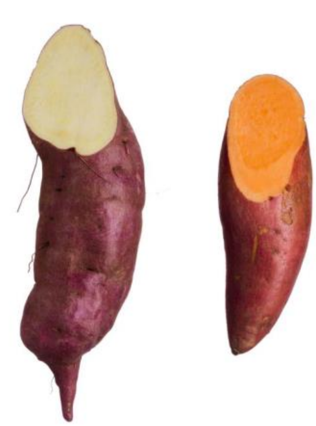
Grower Acceptance

Growers need to be at the forefront of biofortification research because their livelihoods depend on their field production, and, therefore, the success of biofortification implementation. Gaining grower acceptance is important because 40% of the world's population depends on their own food production or narrowed foreign resources (Johns & Eyzaguirre, 2007). The main concern of growers is producing a high yielding crop of adequate quality. Consequently, they are unlikely to grow crops that require expensive inputs or have low yield regardless of other beneficial characteristics because it is not advantageous to them in an economical sense. Also, growers are knowledgeable in what consumers like, so they will not plant crops that they do not think will sell in the market. For example, in a study conducted in Uganda on the adoption of OFSP among farmers, it was determined that yield, taste, and price were the main factors that determined its adoption (Talsma, 2017). This finding is important because it shows that farmers critically examine the product, and they will not use it if it does not meet their standards. Biofortifying crops often changes the taste, texture, and color of the product. Because of this, it is important that researchers share this with farmers so that it gains cultural acceptance before more time and energy is spent on developing biofortified seed that ultimately will not be used. There are other concerns that farmers have when it comes to planting biofortified crops. For example, some farmers use specific varieties due to their religious affiliation, lower labor requirements, or connection to certain health qualities which are a higher priority to them rather than new qualities others are telling them are important (Johns & Eyzaguirre, 2007). This emphasizes the importance of understanding each culture in which biofortification is being. No two cultures are the same; therefore, knowing why certain food systems are being used, religious affiliations of certain crops, and grower priorities will help researchers cater certain biofortified crops to specific areas. Another area to improve upon is making markets more accessible to smallholder farmers. The more access that farmers have to biofortified seed markets, the more likely they are to grow biofortified crops (Lockyer et al., 2018). Overall, the first step in gaining cultural acceptance for biofortification is through the growers because they are the ones that produce the crop on a large scale. By understanding their needs and helping them gain better access to the seed market, there is a greater chance of biofortification providing a sustainable solution to micronutrient malnutrition.

Consumer Acceptance

Once biofortification is implemented by farmers, the next priority is gaining consumer acceptance. There are a number of factors that influence a consumer's decision to use biofortified crops including location, crop type, age, socioeconomic status, and sex (Talsma et al., 2017). Secondary characteristics can also arise that affect the adoptability of biofortified crops such as changes in sensory characteristics (i.e., color, texture, taste) or different preferences of child caretakers. For example, the more a mother likes a particular food, the more likely she is to feed it to her children. To determine the potential acceptance of biofortified crops, two models can be employed. The Theory of Planned Behavior (TPB) and the Health Belief Model (HBM) are combined to study food and health related behavior. The TPB model assumes that the intention to perform a specific behavior is related to the actual behavior whereas the HBM model predicts the acceptance of recommendations for health-related behaviors. Together, these models can help determine the likelihood of consumer acceptance (Hummel et al., 2018). After biofortified crops have been implemented, effectiveness studies can be used to determine acceptance and adoptability of biofortified crops over a period of time (Talsma et al., 2017). Knowing what determines the likelihood of acceptance as well as understanding how to test for it helps develop new implementation strategies for a variety of crops.

Many countries have tried adding biofortified crops into their diet with varied success. One example to consider is OFSP. OFSP is biofortified with beta-carotene which is then converted to vitamin A in the body. Vitamin A deficiency is common in many countries where malnutrition is present, therefore OFSP provides a potential resource for combatting the issue. According to Hummel et al., OFSP have distinguishable



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visual characteristics such as its deep orange color. While the color indicates its increased nutritional quality (high beta-carotene levels and low dry matter content), the changes can impact its cultural acceptability. These trait changes still have to maintain the crop's acceptability if it is to be used to increase vitamin A quantity in consumer diet (Hummel et al., 2018). Many countries have tried implementing it including Malawi, Mozambique, and Uganda. These countries have studied OFSP adoption in their society. In both Uganda and Mozambique, it was found that OFSP was more readily adopted where OFSP information had been actively promoted and participation was encouraged. Additionally, although both the orange and white sweet potatoes were consumed in Uganda, consumers were willing to pay a 25% premium for the orange sweet potato after learning its nutritional information (Talsma et al., 2017). Other factors contributed to acceptability such as the fact that children were found to be more likely to be more accepting of OFSP than adults (Siwela et al., 2020). Cultural and demographic factors determine acceptability, so understanding these factors in each location is imperative. Studying each country-crop relationship and the sociocultural elements that influence acceptance helps in location adoptability (Hummel et al., 2018). The major takeaway is that OFSP has strong nutritional quality that would help alleviate vitamin A deficiency, so understanding the cultural implications of its use as well as promoting its benefits will be one of the best ways to ensure its adoption.

Other biofortified crops have been introduced with a varying degree of success. For example, yellow cassava was introduced in northeastern Brazil, and it had greater success in the older population due to them having a perceived higher understanding of their health, more trust in authorities, and greater access to the media. On the other hand, yellow maize was introduced in Zimbabwe and South Africa, and studies showed that cultural acceptability was low due to a bad taste after storage and its association with food aid and considered use for animals or low-income people (Talsma et al., 2017). Other locations have seen positive acceptance of maize as well as sweet potato and cassava. Results, therefore, are considered context specific. This highlights the importance of conducting sensory evaluation research in each location to help identify differences in consumer preference (Hummel et al., 2018). To improve cultural adoptability going forward, greater consideration should be put on local crops so that consumers utilizing traditional diets have greater access to biofortified foods (Johns & Eyzaguirre, 2007). Understanding each specific location, its socioeconomic climate, their nutritional needs, and local preferences will enhance consumer adoptability of different biofortified crops.

Political/Community Involvement

Once growers and consumers approve of biofortified crops, garnering political and community involvement is the next phase for successful implementation. Combining agriculturalists, nutritionists, economists, sociologists, policymakers, and consumers in community trials is key in community intervention strategies such as biofortification implementation. Everyone should be a part of designing and administering the trial, understanding the trial's results, and using the results to create an action plan for the future (King, 2002). Also, linking the agricultural sector with the health sector helps healthcare workers promote different biofortified crops depending on the growing season and providing the corresponding nutrition information to their patients (Bouis et al., 2013). Also, combining the public sector, private sector, and community organizations help improve management, advocacy, and implementation (Olson et al., 2021). Strong community involvement increases understanding and improves relationships for better biofortification acceptance going forward.

Education and Promotion

The final step in successfully incorporating biofortification is awareness, education, and promotion. Community nutrition programs are critical in increasing consumer acceptance of biofortified crops and food (Siwela et al., 2020). Greater awareness is necessary for healthy food processing and consumption that enhances micronutrient retention in the body (de Valença et al., 2017). For example, in a study conducted in six Nigerian states, only 48 (16%) of 300 subjects had heard of OFSP (Talsma et al., 2017). Although the study was not conducted on a large scale, it does show that effort should be put into increasing public awareness. Careful consideration, however, needs to be made when creating the messaging because one of the biggest barriers to consumer participation is information overload. Instead, a smaller number of messages backed with several different methods of delivery were proven to be more effective in initiating change based on behavioral change studies (Bouis et al., 2013). When creating these messages, an additional point of consideration is who the target group is. Nutrition education needs to be catered to different groups (i.e., children, current or expecting mothers, elderly) in order for the information to be properly understood by everyone (Siwela et al., 2020). For example, in a study published in "Sensory and cultural acceptability tradeoffs with nutritional content of biofortified orange-fleshed sweet potato varieties among households with children in Malawi", information specific to vitamin A and vitamin A deficiency was more likely to prompt caregivers to provide OFSP to their children compared to simply general health knowledge (Hummel et al., 2018). Context-specific messaging has also been implemented to correlate the orange color of OFSP to improved nutrition and health. It then became a selling point to attract consumers in the baked product and snack market (Bouis et al., 2013). After growers, consumers, and community groups approve of biofortified crops and foods, effective promotional and educational programs will help guarantee the long-term sustainability of biofortification strategies.

Ethics

Introduction

The success of biofortification as a strategy to combat micronutrient malnutrition relies on its widespread acceptance. One of the barriers to its acceptance is its ethical impact. If biofortification's negative impact on ethics is greater than the perceived benefits, it will not be accepted or adopted. The Food and Agriculture Organization (FAO) has identified six main ethical issues related to biofortification that require attention: perceived risks and benefits, equity, food safety, accountability, environmental impact, and transparency (Johns & Eyzaguirre, 2007). There is a mutual understanding between producers, consumers, and the market that producers will not produce what consumers will not buy due to a lack of demand, and consumers will not eat food that they feel is unsafe or poorly regulated. Therefore, if biofortification is going to be successful, more resources need to be dedicated to educating both producers and consumers about the manner in which their food is produced. Some of the major ethical concerns frequently cited in literature include how biofortification is approached by authority figures, the argument of genetically modified crops, fear of reduced biodiversity, and fear about food safety and regulation.

Approach to Biofortification

The target of biofortification is to decrease micronutrient deficiency in the world's population, which disproportionately impacts the rural poor; however, biofortification is usually examined with a "technology push" approach. When using a technology push approach, a majority of the people impacted by micronutrient deficiency cannot access the solutions provided. If technology intensive solutions are created, it is likely to be disadvantageous to poor farmers because they do not have the means to access the technology. Additionally, it will benefit rich and commercial farmers who can afford the advancements which brings into creates distributive justice concerns. Because farmers are the ones producing the food for everyone, if new technology (i.e., biofortified seed) is not affordable, the poverty gap remains the same and biofortification processes do not progress (Korthals, 2011). This would negatively impact the economy because poor farmers make up a majority of the farming population and a high population of people farm in some capacity in rural areas. Poor farmers should be the focus of much of the research because they make up 75% of the people living with malnutrition (Korthals, 2011).

A second issue with the way biofortification is approached is that micronutrient malnutrition is often viewed only as a health issue when it is actually a cultural, physiological, and agricultural problem (Korthals, 2011). Approaching biofortification as strictly a health issue is dangerous because it does not take into account consumer preference, environmental impact, or individual community needs. While it is important to focus on the nutritional component of biofortification, it needs to be viewed holistically if it is to be successful long term. Korthals et. al. suggests viewing biofortification with a “pragmatic ethical approach” which would also allow a greater focus on social and ethical beliefs such as biodiversity, food preferences, sustainable agriculture, and ecofriendly emission rates (Korthals, 2011). Bridging the gap between producers, consumers, medical experts, and policy makers will help alleviate ethical issues with the way malnutrition and biofortification are approached.

The Argument Against Genetically Modified Crops

Another major ethical concern related to biofortification is resistance to genetically modified crops. There have been many rewarding outcomes of using genetically modified crops, but if they are not accepted or consumed, then they will not be beneficial in solving the issue of micronutrient deficiency. First, there are concerns with what to call biofortified crops and how to label them. According to the rules of the European Union and the United Kingdom, using conventional breeding methods to biofortify crops is not considered genetically modified. As long as the information is straightforward and factual, they allow the use of a descriptive name if there is no given legal name (Lockyer et al., 2018). On the other hand, through the process of genetic engineering, transgenic plants (also known as genetically modified organisms) are made (Singh et al., 2016). Genetic engineering is utilized when a crop does not naturally produce a desired micronutrient. The new gene can come from all available sources (Singh et al., 2016), and genetically engineered crops can be created using processes such as overexpression of current genes, inhibiting gene synthesis pathways, downregulating specified gene expression, and introducing genes from one source into the crop genome (Malik & Maqbool, 2020). Because new genes are being introduced, the plant's genome is manually changed. According to Singh et. al., some of the centralized goals of biofortification are to reduce the amount of antinutrient compounds, increase mineral mobilization in the soil, and increase the status of nutritional enhancer compounds (Singh et al., 2016). There have been a number of transgenic crops that have been produced including maize, soybean, rice, pea, tobacco, potato, wheat, strawberry, cassava, barley, tomato, and mustard (Malik & Maqbool, 2020).

There have been advancements in the use of genetic engineering as it relates to biofortification; however, it still lacks widespread support due to expensive and tedious regulatory procedures, political disapproval, and complicated legal structures for commercialization. This is evident through the example of golden rice. Golden rice has been modified to increase its production of vitamin A, and it now has the ability to produce more than 50% of the estimated vitamin A required for good nutritional status. Although it was put on the market in the early 2000s, as of 2020, it was not commercially available in any country because of the approval process and fear of human and environmental health concerns (Jha & Warkentin, 2020). While genetically modified crops introduce great potential in combating human micronutrient deficiency, greater emphasis should be put on both understanding consumer wants, as well as, educating them in order to gain a better idea on biofortification adoption potential. Consumer freedom to choose what they eat is valid, therefore, obstacles posed by genetic modification should be explored further.

Food Safety

Food safety is another contentious topic when it comes to biofortified crops. Because the crop's natural genome is being altered, questions about the safety of the crop arise because it is considered unnatural. Currently, there is very little evidence regarding the safety of biofortified crops that are currently on the market for both human and animal consumption, therefore, extra care should be used when communicating with the public about proper consumption (Garcia-Casal et al., 2016). Many consumers need to be educated on both the nutritional benefits of increased micronutrient intake, as well as cautions against excessive micronutrient intake. There are many different food sources people can utilize to receive healthy amount of micronutrients, so nutrition education is needed. Additionally, genetically modified foods have received public backlash for concerns regarding the allergenicity of new proteins incorporated into their genomes; however, as of 2007, there had not been any reports of allergic reactions in countries where the presence of genetically modified foods was greatest (Johns & Eyzaguirre, 2007). Food safety is a significant ethical matter, therefore, educating consumers on their right to informed choice is imperative. By educating the community, it both guarantees agronomically, economically, and culturally accepted crop lines, and also increases investments made by stakeholders because there is evidence that they are backed by the community. Educating the farmers about what they are planting is also important. Local farmers in rural communities where biofortification efforts are mainly focused often do not have a significant amount of information related to the varieties they are planting. They are less likely to make planting decisions without sufficient information (Johns & Eyzaguirre, 2007). If they are going to be planting biofortified seed, biofortification safety and health education should be mandated.

Concern for Biodiversity

Conserving biodiversity has become a major point of interest recently as species start to face the threat of extinction. Biodiversity is defined as the entire variety of species living on Earth (National Geographic Society, 2019). Genetically modified crops are being evaluated for their expansion of biodiversity erosion (Johns & Eyzaguirre, 2007). This concern is attributed to the idea that, as the planting of biofortified plants increases due to their superior nutritional quality, there will be a decline in the presence of other varieties (Johns & Eyzaguirre, 2007). There is also fear that cross-contamination will occur between biofortified and non-biofortified varieties which will consequently impact farmers and crop variation (Garcia-Casal et al., 2016). It is plausible that ecologists and conservationists would have some pushback on the implementation of biofortified varieties if these concerns are valid. Biodiversity is important to maintain the gene pool on Earth, and by preserving it, worries related to species extinction are diminished. Considering that this is frequently cited as a barrier to biofortification implementation, it should not be overlooked when creating application strategies.

Biofortification Regulation

Lastly, ethical concerns regarding the regulation and involvement of biofortification should be evaluated. There are several groups who are both opposed to putting biofortification into practice as well as some who are neutral on the subject. Clear communication with both sets of people will help make sure the information presented to the public is accurate. It will also assure that opponents of biofortification cannot influence peoples' decision with false information. Equal access to biofortification technology and products needs to be granted to all farmers and consumers in order to realize its intended effect. Involving farmers and community members alike throughout the entire research and implementation process will help increase consumer acceptance because it allows them to have a say in dietary choices and food justice (Garcia-Casal et al., 2016). It is important to note that consumer opinions are valid when it comes to deciding what they eat, and it is fair to determine that they do not want to consume genetically modified foods. Ensuring that true information is being presented, allowing all people to stay involved, and regulating the use of biofortification technology can help mitigate ethical concerns in respect to biofortification.

Future Work

Introduction

The future success of biofortification depends on its ability to overcome its barriers related to labeling, environmental factors, government acceptance, technology, and community education. Biofortification as a solution to hidden hunger is growing. As of 2021, more than 30 countries have distributed different biofortified crops such as iron fortified beans and pearl millet, vitamin A fortified orange sweet potato, orange maize and yellow cassava, and zinc fortified rice and wheat (HarvestPlus, n.d.). Additionally, HarvestPlus has tested or released over 290 varieties of biofortified food crops (Jha & Warkentin, 2020). Now that research is being conducted globally with positive results, the next step is to combat multi-nutrient deficiencies by developing crops with increased levels of several nutrients without harmful interactions (Singh et al., 2016) while simultaneously utilizing technology to produce on a large scale (Lockyer et al., 2018). To improve bioavailability, the nutrient concentration and absorption needs to increase as well as the crops' genetic diversity. This can be achieved through reducing antinutrients such as phytate and polyphenols, and raising the level of promoters such as vitamin C, cysteine, methionine, and lysine (Jha & Warkentin, 2020). Once the nutritional components are achieved, the secondary factors can be addressed.

Potential Barriers

The extensive research on biofortification has been conducted with the ultimate goal of acceptance and implementation to alleviate hidden hunger and its subsequent diseases. As progress has been made researching and developing these crop lines, leaders are turning attention to its application to society, but certain barriers are arising impacting its current and future success. First, certain environmental conditions are creating a setback. Drought is currently the biggest yield-limiting factor, yet many places in need of a micronutrient malnutrition solution have low levels of rainfall. To overcome this obstacle, plant breeders need to introduce drought-tolerant cultivars as candidates for biofortification study (Siwela et al., 2020). Also, improving soil quality that allows for more efficient mineral mobilization, uptake, and transportation will increase the efficacy of current biofortified varieties (Singh et al., 2016). Lastly, processing postharvest has a large impact of bioavailability. For example, greater amounts of nutrients can be lost from the grain of seed crops during milling, polishing, and cooking (Jha & Warkentin, 2020). Improving current processing techniques would also improve the bioavailability and overall success of biofortification.

A second major barrier that has a foreseen impact on the success of biofortification is government regulation and policy. First, the government in which implementation is occurring needs to provide proper financial resources in order to establish the program (Garcia-Casal et al., 2016). Securing government funding is often a long process, and it usually requires many people to approve of the allocation of money. Additionally, implementing policy that creates a strong relationship between the health, environmental, and agricultural sectors is necessary to combine biofortification with traditional food systems and nutrition education programs (Johns & Eyzaguirre, 2007). The relationship between the public and private sector also needs to be amended. Currently, the private sector left several gaps such as not prioritizing biofortification to certain ecologies or crops local to specific areas (Johns & Eyzaguirre, 2007). Additionally, there are also regulations currently in place that strictly watch nutrient levels in food to maintain food safety. New protocols will likely need to be added to the existing regulations so that biofortified crops with increased nutrient levels can be accessed on a larger scale (Malik & Maqbool, 2020). This includes deciding on proper labeling. Because they include a greater amount of nutrients, different labeling is being considered; however, there are also questions regarding if they should be labeled as genetically modified or as a different category all together (Campos-Bowers & Wittenmyer, 2007). The label should adequately inform the consumer on what is in the food without including false information or being misleading. Regardless, deciding on how the food will be labeled pushes biofortification closer to implementation. Addressing the current setbacks and foreseeable future barriers will increase the likelihood of successful adaption and acceptance of biofortification going forward.

Education and Promotion

As biofortification starts to make its way into the food system across cultures, education and promotion will be necessary so that consumers understand its benefits and drawbacks, proper use, and potential implications for the future. There are already a number of community health programs in place in several countries, so adding nutrition education as it relates to biofortification provides a feasible strategy to begin this process (Siwela et al., 2020). Nutrition education and related activities can also be added to school curriculums so that children are exposed to biofortification information, and they can begin to develop their food preferences (Garcia-Casal et al., 2016). The information sessions would help garner support and improve consumer attitude towards consumption (Hummel et al., 2018). There are a number of proposed ways for information to be spread including community nutrition fairs, radio station talk shows, cooking lessons, and creating shareable recipes. For example, data from Uganda and Zambia suggested that activities such as radio shows and distribution of meals made with biofortified crops improved the adoption of biofortification (Garcia-Casal et al., 2016). Also, cooking lessons have shown great potential in helping with biofortification adoption in both consumer acceptability as well as showing parents how to incorporate biofortified crops into baby foods (Siwela et al., 2020). As people learned how to use biofortified crops in a way that satisfied them, their acceptance increased. One final promotional activity that is being studied is the creation of home gardens with biofortified crops. The main idea is that if the biofortified crops are grown at home where they can be conveniently accessed, families are more likely to consume them (Siwela et al., 2020). This solution appears promising, but it requires families to have adequate resources to maintain a garden of sufficient quality to serve themselves. Education and promotion are important components to the application of biofortification because it alleviates consumer fears, and it expands their nutritional understanding so that ultimately micronutrient malnutrition is decreased.

Potential

Biofortification has shown strong potential to benefit humans, animals, and the environment (Campos-Bowers & Wittenmyer, 2007) while also being a cheaper alternative to other intervention strategies (Siwela et al., 2020). Although major cereal crops have currently been the subject of a majority of the biofortification research, other crops, such as yams, bananas, and other roots and tubers, show potential for biofortification. This is important due to their prevalence in traditional food systems (Johns & Eyzaguirre, 2007). As the aforementioned obstacles are eliminated, biofortification as a strategy for micronutrient malnutrition alleviation gains potential as a successful option.

Conclusion

This research aimed to highlight the benefits and detriments of implementing biofortification as a sustainable solution to hidden hunger. Because the world's population is continuing to grow and micronutrient malnutrition is a large threat to human health and well-being both now and in the foreseeable future, researchers are searching for potential long-lasting solutions. Biofortification demonstrates strong potential both nutritionally and environmentally which has been supported by numerous studies. On the other hand, studies have shown the need to emphasize cultural and ethical views as well because they pose significant barriers to successful large-scale adoption. Based on the research conducted, if biofortification can overcome certain barriers, it is a strong candidate to be used to fight micronutrient malnutrition. This would require work on all sides of the spectrum including better education for growers and consumers, collaboration between different government sectors, and greater understanding of each site's cultural and ethical values as well as their traditional food systems.

Through this research, it is apparent that solving the issue of hidden hunger is not direct but rather it requires a multi-faceted approach. These considerations provide valuable information for researchers and community members alike because it helps people gain a deeper understanding of others and their needs. When brainstorming solutions for others, it is important to keep their lifestyles in mind, otherwise the solution will not be successfully adopted. Additionally, once the solution has proven to be successful, teaching others how to sustain it on their own is necessary. If people can maintain biofortification on their own, it provides nutritional benefits to help alleviate malnutrition in their society, it provides environmental benefits to improve soil and plant quality, and it positively contributes to the economy. These aspects are important because traditionally, communities that have high rates of malnutrition also suffer from poor land conditions and weak economies. In that manner, while biofortification requires a multifaceted approach for its successful application, it also produces more solutions than just nutritional benefit.

Going forward, it will likely be useful to apply biofortification methods to traditional crops in order to maintain the country's biodiversity. Much of the initial research has been focused on major staple crops because they are consumed in large quantities; however, a good next step would be to include crops that are common in individual areas. This may help with acceptability among growers and consumers. Also, creating more awareness and promotion campaigns for biofortification in rural areas will help reach a greater number of people. Looking at different studies showed how a high percentage of people did not know about biofortification even though it was providing solid results. Therefore, this expressed the need for greater information dissemination in many areas.

To combat hidden hunger, biofortification stands out as a current leading solution. Although it still has some barriers that need to be overcome for successful adoption in many communities, it is headed in the right direction. The United Nations defines the right to food as the following:

> The right to food is the right to have regular, permanent, and unrestricted access—either directly or by means of financial purchases— to quantitatively and qualitatively adequate and sufficient food corresponding to the cultural traditions of the people to which the consumer belongs, and which ensure a physical and mental, individual, and collective, fulfilling, and dignified life free of fear. (OHCHR, n.d.)

Both nutrient-dense and sufficient food quantity that strongly associates with peoples' cultural standard is a right to life. With continued work on biofortification, it provides a promising solution to make this right a reality for billions of people around the world.

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