



REVIEW ARTICLE

# Bio-fortification in crops, recent approaches, challenges and future strategies: A review

Durga Prasad<sup>1</sup>, Ajay Kumar Srivastava<sup>2</sup>, Jyoti Yadav<sup>3</sup>, Namami Gohain<sup>4</sup>, Bhartendu Yadav<sup>5\*</sup>, Roop Kumar<sup>5</sup>,  
Atin Kumar<sup>6</sup>, Amita Yadav<sup>7</sup> & Shalini Singh<sup>3</sup>

<sup>1</sup>Department of Genetics and Plant Breeding, Chandra Shekhar Azad University of Agriculture & Technology, Kanpur 208 002, Uttar Pradesh, India

<sup>2</sup>Department of Agricultural Economics and Statistics, Chandra Shekhar Azad University of Agriculture & Technology, Kanpur 208 002, Uttar Pradesh, India

<sup>3</sup>School of Agriculture, Galgotias University, Greater Noida 203 201, Uttar Pradesh, India

<sup>4</sup>Department of Economics and Sociology, Punjab Agriculture University, Ludhiana 141 027, Punjab, India

<sup>5</sup>Department of Agricultural Economics and Extension, Lovely Professional University, Phagwara 144 411, Punjab, India

<sup>6</sup>School of Agriculture, Uttarakhand University, Dehradun 248 007, Uttarakhand, India

<sup>7</sup>Faculty of Agricultural Sciences, GLA, Mathura 281 406, Uttar Pradesh, India

\*Correspondence email - [yadvbhartendu@gmail.com](mailto:yadvbhartendu@gmail.com)

Received: 08 July 2025; Accepted: 23 September 2025; Available online: Version 1.0: 26 February 2026

**Cite this article:** Durga P, Ajay KS, Jyoti Y, Namami G, Bhartendu Y, Roop K, Atin K, Amita Y, Shalini S. Bio-fortification in crops, recent approaches, challenges and future strategies: A review. *Plant Science Today*. 2026; 13(sp1): 1-9. <https://doi.org/10.14719/pst.10511>

## Abstract

Micronutrient deficiencies such as folic acid, carotenoids, selenium (Se), zinc (Zn), iron (Fe) and iodine (I) affect individuals globally, posing significant challenges to human health and development and so become a major concern for the future. Involvement of modern practices such as plant breeding and genetic engineering in biofortification has become a sustainable answer for these deficiencies. This strategy is particularly beneficial for the health of low-income people with limited access to commercially fortified foods. With a one-time investment and the ability for farmers to propagate seeds at minimal cost, biofortification offers a promising avenue for long-term nutritional improvement. Recent advancements have seen the introduction of biofortified crop varieties through targeting various macro and micronutrients, antioxidants and other bioavailable components. Despite its potential, biofortified crops encounter obstacles related to development, distribution and consumer acceptance. Overcoming these challenges is crucial for optimizing the utilization of biofortified foods and achieving widespread impact in combating malnutrition and starvation worldwide.


**Keywords:** biofortification; genetic engineering; hidden hunger; micronutrient; plant breeding

## Introduction

Micronutrients, such as selenium (Se), zinc (Zn), iron (Fe), iodine (I) and folic acid, are crucial for the growth and development of humans because they support several metabolic processes like digestion and assimilation. A large portion of the global population relies on meals based on plants, which are frequently lacking essential micronutrients (1) and frequently fall short of the recommended dietary allowance (RDA) for certain micronutrients. One in 3 individuals worldwide struggle with a deficiency of micronutrients, which is also known as "hidden hunger". The definition of hidden hunger is more like an elucidation. The challenge of hidden hunger, the 2014 Global Hunger Index, asserts that: "Deficiency of micronutrients, usually known as hidden hunger, is a type of undernutrition that develops when intake of vitamins and minerals is inadequate to support adults' normal mental and physical wellness and development as well as children's excellent health and development. Poor diet, illness, or increased

micronutrient requirements not satisfied during both stages of pregnancy and lactation are some of the causes" (2). However, incorporating health-related elements and minerals into a meal could be viewed as a tactic to combat malnutrition or address a particular nutritional need (3).

The only way to enhance the nutritional value of Agricultural products before harvest, in the case of unprocessed agricultural products, is to adopt superior genotypes or certain agronomical practices (4). Enhancing the nutritional value of grains through a variety of techniques, such as altering crop agronomic practices, traditional plant breeding and cutting-edge biotechnology alternatives (Fig. 1). It became utmost important, after the establishment of targets of sustainable development goals, including undernourishment, obesity and overweight and diet-related, non-contagious conditions. The increasing demand for the addition of mineral elements to fresh food articles for consumption by humans has sparked active research with a focus on developing appropriate application techniques.



DIVERSIFIED DIET	<ul style="list-style-type: none"> <li>• Consumption of different food groups</li> <li>• Prevent nutrition deficiencies</li> </ul>
FOOD FORTIFICATION	<ul style="list-style-type: none"> <li>• Addition of nutrients to commonly consumed food</li> <li>• Costly</li> </ul>
BIOFORTIFICATION	<ul style="list-style-type: none"> <li>• Crops with improved micronutrient content</li> <li>• Cost effective and feasible</li> </ul>

**Fig. 1.** Comparison of nutritional approaches: Diversified diet, food fortification and biofortification.

This article encompasses advancements in the biofortification of agri-food products for number of essential minerals, which include Cu, Se, Mg, iodine (I), calcium (Ca), Zn, Fe and silicon (Si), which are frequently absent or insufficiently present in human diets. This review intends to describe and bring to light the effective agronomic ways to enhance the quantity of the evaluated minerals in the cooked form of food articles (grains, fruits and vegetables) after their perceptive role in the physiology of plants and human nutrition.

#### What is bio-fortification and why is it needed?

Different methods are used to attenuate micronutrient malnutrition; the most prevalent are fortification and supplementation of products (5). Biofortification, which involves using plant breeding to improve micronutrients, is one approach to addressing hidden hunger and deficiencies in micronutrients. We use the term "biofortification" to describe a genetic modification of a vegetation to increase the level of selected micronutrients in the crop, in contrast to "fortification," which is the incorporation of nutrients, such as iron to wheat flour or iodine to salt. Agronomic biofortification, which involves adding nutrients to leaves or soil to boost their concentration in food, is also not included (6). Conventional crop breeding and selection have been mostly responsible for biofortification, whilst direct genome modification has also been used, as in the case of Golden Rice (7).

This type of biofortification is centred on a straightforward set of guidelines. There are more than 2 billion undernourished people. Particularly, the poor cannot afford the varied diets that would provide sufficient micronutrients. Increase the micronutrient content of staple crops by biofortifying them. The HarvestPlus research programme of the Consultative Group on International Agricultural Research (CGIAR), which concentrated on enhancing vitamin A, Fe and Zn in several starch-rich cereals, root and tuber crops, has been largely responsible for the worldwide research effort on biofortification. The development of beans rich in Fe, millets and cowpeas, maize rich in Zn, rice and wheat, as well as maize, cassava, bananas, plantains and sweet potatoes, which are rich in vitamin A, by HarvestPlus and its affiliates, is ongoing to date (8).

Genetic and agronomical techniques, which can be used via transgenic techniques or conventional breeding, are 2 among the various ways to produce biofortified crops (9, 10). The primary objectives are to enhance the amount of minerals or other nutrients in the edible portion. Transgenic programmes involve biotechnology research which allows the genetic modification of a species to develop a plant with desired characteristics (such as a higher

concentration of specific nutrients). This method is used very least, despite long-term cost-saving potential, because the research and development are still so sluggish and expensive. In developing countries such as India, it offsets higher costs to the cultivation of the biofortified vegetables, like the development of a premium product with greater nutritional content, able to satisfy the new consumers' demand, ready to pay for a healthy way of eating (11). Furthermore, various countries (Germany, Italy, etc.) have strong legal restrictions that prohibit genetically modified organisms (GMOs). In the same line, to introduce desired qualities in new cultivars that are present in plants naturally, crossing between various genotypes is possible. New kinds with a greater amount of specific nutrients have been produced traditionally using a genetic breeding approach for many years. In the current instance, the restriction is to find the needed traits among the genetic resources at hand (12).

#### Genetic engineering approach

Whenever a particular micronutrient is not produced naturally in the crops, changes in the necessary characters are not commonly accessible in the readily accessible germplasm and changes can't be conventionally acquired through breeding. Hence, genetically engineered biofortification provides a second approach (13). This method can be used to concurrently target the elimination of antinutrients and the incorporation of promoters that can increase the bioavailability of micronutrients in addition to boosting the concentration of microelements (14). This method employed genes from bacteria as well as other species, in addition to those connected to different metabolic pathways used by plants (15). A transgenic strategy has been used to successfully modify several crops to address micronutrient scarcity.

#### Conventional plant breeding approach

Plant Breeding methods are one among the sustainable and cost-effective approaches of biofortification, which can enhance the health of impoverished people worldwide (16). This strategy has been utilized for treating micronutrient deficiencies, such as those involving carotenoids, Fe and Zn. For the plant breeding approach to biofortification to be successful, there must be genetic variety in the gene pool. Various studies have divulged that the quantity of minerals and vitamins in diverse crops varies significantly. Screening a large variety of germplasms can identify parental genotypes that have elevated micronutrient concentration and they could be used in crosses and also for the creation of molecular markers to aid marker-assisted selection in breeding and genetic research. To find out about the genotype and environment interaction (GxE),

promising lines might be examined in several different places (17). Through conventional plant breeding techniques, research has been undertaken on crops to increase essential micronutrients like carotenoids, Fe, Zn, Se, I and folates.

### Agronomic approach

The supplementation of essential nutrients as inorganic compounds through fertilization has proven effective in elevating the mineral-related content of vegetations like wheat, rice and maize (18). Nonetheless, implementing this strategy universally confronts challenges due to the costs associated and variable crop responses contingent upon the properties of the nutrient and the specific characteristics of the crop.

### Micronutrients involved in biofortification and their sources

#### Sources of micronutrients

In general, the macronutrients (proteins, carbs and fats) and micronutrients (vitamins, minerals and other elements needed in precise quantities) present in the foods ingested as part of an eclectic diet vary. When accessible, staple meals provide nearly all the diet's macronutrients and are eaten once or more during the day; however, which foods are considered staples depends on culture. These social standards, religious perspectives and socioeconomic practices differ widely between nations and also express how much

**Table 1.** Micronutrient fortification in common crops

Micronutrient	Crops	Reference
Calcium (Ca)	Finger millet	(20)
	Basil	
	Lettuce	
Magnesium (Mg)	Onion	(21)
Iodine (I)	Chinese cabbage	(22)
	Carrot	
	Cowpea	
Zinc (Zn)	Kale	(23, 24)
	Lettuce	
Selenium (Se)	Radish	(25, 26)
	Tomato	
Iron (Fe)	Potato	(26)
	Tomato	
	Chard	
Silicon (Si)	Green bean	(27, 28)
	Kale	
Copper (Cu)	Spinach	(29)

influence women have (19). Animal-based meals can be excellent sources of calories, protein and minerals, but they are frequently inaccessible to the most vulnerable households. Overall, the world's meals have become more uniform, relying more on fewer varieties of grain crops that are crucial to the international economy (Table 1).

### Micronutrients commonly involved with the bio-fortification of various crops

#### Calcium

The mineral Ca is mostly linked to strong bones and teeth, but it also has a significant impact on muscle contraction, regular heart rhythms, blood clotting and neuron function (20). The RDA for Ca is 1000 mg for women aged 19 to 50 and 1200 mg for women aged 51 and beyond. The RDA for pregnant women or nursing women is 1000 mg. The RDA is 1000 mg for men aged 19 to 70 and 1200 mg for men aged 71 and beyond. The body stores 99 % of its Ca in the

bones, with the rest 1 % being found in other tissues such as blood, muscle and other tissues. Deficiency symptoms include numbness or tingling in fingers, abnormal heart rate, muscle cramps or weakness and poor appetite.

#### Magnesium

The mineral is important for assisting over 300 different enzymes in carrying out various chemical reactions in the body, including those which produce proteins and robust bones, control blood pressure and sugar and maintain nerve function and healthy muscles. It also functions as an electrical conductor, which causes the heart to beat steadily and contract muscles. For individuals aged 19 to 51 and over, the RDA is 400–420 mg for men and 310–320 mg for women per day. About 350–360 mg per day is needed for pregnancy, while 310–320 mg is needed for lactation. Our bodies store over half of all the Mg we contain in bones and the rest is stored in different body tissues. Deficiency symptoms include nausea, vomiting, fatigue, weakness, poor appetite, numbness or tingling in the skin, Muscle cramps, abnormal heart rate and seizures (21).

#### Iodine

Thyroxine (T4) and triiodothyronine (T3), the thyroid hormones, are dependent on I, which is also necessary for healthy growth, development and metabolism. According to the Food and Nutrition Board of the Institute of Medicine, the recommended daily intake (RDI) of I<sub>2</sub> for adults is 150 µg. I deficiency results in goitre, hypothyroidism, mental retardation, cretinism, decreased fertility and higher rates of neonatal and perinatal mortality. It is essential for the development of brain; deficiency during pregnancy might result in cognitive problems in the offspring (22).

#### Zinc

Another essential mineral that humans require is Zn. It has a significant role in various biological processes, including cell proliferation and growth, wound healing, membrane signalling systems, quenching reactive oxygen radicals to prevent oxidative damage to cells and lowering the risk of malignancies such as pancreatic and prostate cancer. The recommended daily allowance (RDA) of Zn for adults is 8 mg per day for females and 11 mg per day for males. A poor immune system, frequent infections, mental disease, stunted growth and infertility are among the effects of Zn deficiency (23–25).

#### Selenium

Selenium is a micronutrient, crucial for growth, also shields the body from disease, oxidative stress and the spread of cancer. The recommended daily intake (RDI) for selenium is 55 g day<sup>-1</sup> for males as well as females. Se deficiency in the humans' body is connected to various conditions, including Keshan, Keshin-Beck and myxedematous cretinism (26).

#### Iron

Life forms require Fe, which is essential for several metabolic activities like electron transport and the production of deoxyribonucleic acid (DNA). The human body needs Fe to create the oxygen-transporting proteins haemoglobin and myoglobin, as well as the enzymes needed for electron transfer, as well as oxidation-reduction reactions (27). The RDA for Fe is 8 mg for adult males and 18 mg for adult females, as determined by the Food and Nutrition Board (Institute of Medicine), National Academy of Sciences. Lack of Fe can result in fatigue, light cephalgia and unfavourable

pregnancy outcomes, including early delivery, babies with low birth weights, delayed baby growth and impaired cognitive abilities.

### Silicon

The manufacture of collagen and elastin depends on Si, which is also critical for the health of bones, cartilage, tendons, joints and connective tissues. While elastin gives tissues, skin, hair and blood vessels their elasticity, collagen serves as a structure to support the tissues. In actuality, bone is a unique kind of connective tissue. The concentration of Si decreases as the bone ages, while deposits of Ca and phosphorus (P) are simultaneously created. Consequently, it may be said that Si regulates the amount of Ca and P that accumulates in bone tissue. Apart from its involvement in bone and connective tissue health, Si also contributes to other health benefits like preventing aluminium (Al) toxicity and shielding vascular tissue. The recommended daily requirement for Si is between 20–50 mg. A lack of Si can harm the skin and hair, dry out the nails and cause them to break easily. Furthermore, a low Si diet is the consequence of decreased stomach acidity brought on by disease or ageing, which also reduces the body's capacity to metabolise Si from dietary sources. Si supplements should not be taken by expectant or nursing women since they may affect the mothers and their unborn child (27, 28).

### Carotenoids

Plants naturally synthesize colored pigments called carotenoids. Since both humans and animals are unable to synthesise carotenoids, carotenoids must be obtained through diets originating from plants. In the human body, carotenoids function as significant antioxidants and are crucial to many physiological functions. In nature, more than 600 carotenoids are identified. Age-related degeneration is prevented by lutein and zeaxanthin. Lutein lowers the likelihood of cataracts and has a link to lowering cardiovascular disease. Mammals need vitamin A for healthy cell division, development of bone and eyesight. B-Cryptoxanthin suppresses osteoclastic bone resorption while stimulating osteoblastic bone growth.

### Copper

Copper (Cu) supports several enzymes involved in the body's energy production, Fe absorption and breakdown, red blood cell formation, collagen synthesis, connective tissue and neurotransmitter production in the brain. In addition, Cu is necessary for healthy immunological and brain development. It is also a part of the antioxidant enzyme superoxide dismutase, which breaks down dangerous oxygen molecules known as free radicals. For individuals aged 19 years and older, the RDA is 900 µg per day for both men and women. A daily intake of 1300 µg is required during pregnancy and breastfeeding in adults aged 19 years and older, whereas 1000 µg per day is recommended for younger individuals aged 14–18 years. Deficiency symptoms include bone fractures, increased infections, anaemia, high cholesterol, osteoporosis and loss of skin pigment (29).

## Via conventional plant breeding

### Rice

For the poor throughout most of the Asian countries, rice accounts for up to 80 % of their daily energy uptake. The Bangladesh Rice Research Institute (BRRI) and the International Rice Research Institute (IRRI) created rice cultivars with high Zn for India and Bangladesh. The 1<sup>st</sup> breeding objective for polished rice was

established as 24 ppm Zn, which is 8 ppm more than the initial Zn concentration sold commercially. Trials for Official registration are underway in India and Bangladesh for high-yielding cultivars that have achieved over 75 % of the aim; release is anticipated in 2013. An Fe-rich rice cultivar was released in China in 2011 and a high-Zn rice variety was discovered in Brazil and registered for distribution by Embrapa in 2012. According to retention studies, parboiling and milling do not significantly lower the Zn concentration of rice compared to Fe because Zn is more evenly distributed across brown rice grains (30).

The BRRI measured the amount of Zn that was lost from rice throughout the washing and milling process before cooking. Before cooking, washing the milled grain caused about 10 % of its Zn to be lost (31). An additional 10–14 % of the Zn in rice may be lost if it is boiled in too much water, which is then discarded before consumption. Yet no proof of the bioavailability or effectiveness of rice has been biofortified with Zn. The low responsiveness of the concentration of Zn in blood to relatively small quantities of extra Zn consumption makes it difficult to demonstrate the effectiveness of a food-based strategy to upgrade Zn intake. More investigation is needed to determine the effects of Zn therapies on human health, as well as more sensitive biochemical markers of Zn levels (32).

### Wheat

International Maize and Wheat Improvement Centre (CIMMYT), is in charge of developing high-Zn wheat for India and Pakistan. For whole wheat, the target in initial breeding was set at 33 ppm Zn, which is 8 ppm higher than the original baseline Zn concentration. High-Zn wheat's enhanced agronomic qualities over popular varieties are anticipated to propel adoption and breeding efforts have concentrated on increasing Zn content as well as resistance to emerging strains of stem rust and yellow rust. Both India and Pakistan are conducting multilocation trials; the 1<sup>st</sup> release with 75 % of the desired level of Zn is anticipated in India in 2013. In 2011, a variety of wheat was introduced in China that had a Zn concentration of 44 ppm, significantly higher than the desired level.

### Maize

Provitamin A in maize breeding is driven by the CIMMYT and International Institute of Tropical Agriculture (IITA) in collaboration with National Agricultural Research and Extension Systems (NARES) in southern Africa. Germplasm evaluation found genetic variation for the objective level (15 ppm) of provitamin A carotenoids in temperate maize, which was then reproduced into the tropical varieties. Ongoing improvements in marker-assisted selection technology have sped up and precision of recognizing genes controlling the characters of interest in maize. Genotypes that can provide 25 % of the estimated average requirement (EAR) for women and preschool children were released in Nigeria (2 varieties, IITA hybrid A0905-28 and A0905-32) and Zambia (3 varieties, GV662A, GV664A and GV665A) in 2012. A maize variety with comparable provitamin A levels has been registered for release by Embrapa of Brazil in South America. Studies on the storage stability of the 2012-released varieties are still ongoing; however, a prior investigation involving several varieties revealed a 25–60 % reduction in provitamin A following drying along with dark storage for four months at 251 °C.

## Via transgenics development

### Golden rice

Golden rice was the 1<sup>st</sup> to be developed by the Swiss Federal Institute

of Technology and Syngenta continued the research as part of their then-commercial pipeline. After Syngenta settled not to go after the character as a commercial product, transgenic events with greater levels of provitamin A, up to 37 ppm in a US variety-was created and contributed to be utilized by the Golden Rice Network (33). Currently, IRRI is in charge of Golden Rice research. The GR2 events had been backcrossed into varieties for Bangladesh, India, Philippines and Indonesia beginning in 2006. Golden rice has been shown through bioavailability testing to be a useful source of vitamin A for humans, with a projected 3.8:1  $\beta$ -carotene to retinol conversion rate (34).

#### **African bio-fortified sorghum**

Transgenic sorghum has reduced relative bio-accessibility, but the grain's higher carotenoids increased total and provitamin A carotenoids' overall levels of accessibility. Further research on bioavailability has demonstrated that lowering phytate levels increases iron absorption by 20–30% and Zn absorption by 30–40%.

#### **Iodine potato**

Fortified potatoes are a nutritionally enhanced variety of potatoes that have been augmented with additional vitamins and minerals to address nutritional deficiencies in certain populations. The fortification process involves adding essential nutrients such as vitamin A, vitamin C and Fe to the potato, thereby increasing its overall nutritional value. This approach aims to combat deficiencies of micronutrients and improve the health outcomes of individuals who rely greatly on potatoes as a staple food. Fortified potatoes can play an important role in enhancing dietary diversity and addressing specific nutrient needs, contributing to overall public health. Potato has been majorly incorporated with phytoene synthase (PSY) gene and by the incorporation of 3 other genes: PSY, lycopene  $\beta$ - $\beta$ -cyclase and phytoene desaturase (35).

### **Difficulties with bio-fortification**

#### **Dietary diversity**

The fundamental rationale for biofortification fails to acknowledge the significance of dietary diversity in providing sufficient nourishment. It doesn't think to diversify production or diets before jumping straight to biofortified staples (36). When taken as a whole, diet is heavily influenced by culture and is based on historical cultural practices as well as regional farming, seed and market conditions, that is, on what is suitable, readily available, reasonably priced and accessible (37). Numerous recent studies in rich and developing nations have cast doubt on the notion that varied, sustained healthy meals are invariably more expensive than existing diets (38). HarvestPlus has claimed that it will compare biofortification to industrial fortification and supplementation between 2020 and 2030, as well as evaluate health results in addition to micronutrient insufficiency status (39).

#### **Impact on health**

A committee was established by the World Health Organization (WHO) in 2016 to examine data regarding the nutritional effects of biofortification (40). The WHO classified biofortification as a "Category 3 Intervention" on its website in January 2022, stating that "systematic reviews have not yet been conducted" and that "available evidence is limited". "More research is required before specific suggestions and recommendations can be made," the conclusion states (41, 42).

#### **Yield penalty**

Numerous instances of biofortification blend high yield with

elevated micronutrient levels. High-Zn Maize (43), Zn and Fe-enriched wheat (44), etc. Furthermore, new studies show that the yield penalty is still an obstacle. Zn content in rice can be diluted by increasing yield and combination selection for both qualities yields less genetic gain compared to either feature considered alone (45). In cassava and maize, there have been observed negative correlations between yield and  $\beta$ -carotene (46).

#### **Genetic uniformity**

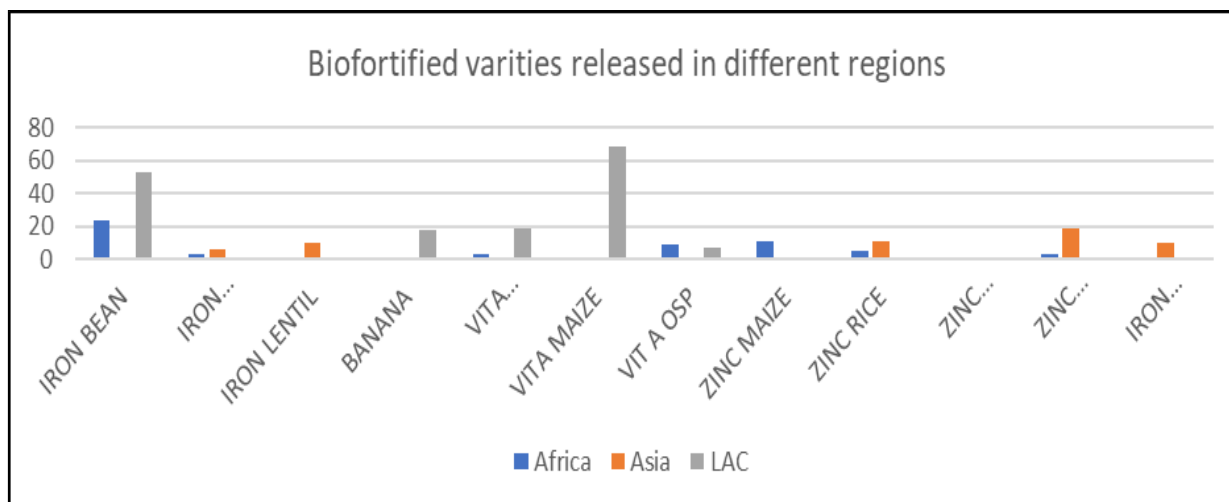
There are certain risks to genetic uniformity which are well known (Late blight of potato, Southern corn blight, Fusarium in banana), also the benefits of genetic diversity are well received in the field of agriculture (47). By continuously backcrossing into a single adapted parent and introducing elevated micronutrient levels into several new types using the same genetic package, bio-fortification helps maintain genetic homogeneity. Breeders can now choose offspring that have the beneficial traits of the recipient (high-yielding) parent through marker-assisted backcrossing, which has emerged as the preferred technique for bio-fortification (48). Near clones of commonly cultivated types are the final result, improving genetic consistency and susceptibility to abiotic and biotic stresses.

### **Delivery and commercialization of bio-fortified crops**

The design of a delivery strategy is influenced by 2 factors: the visibility or unsightliness of the bio-fortified feature and the presence or absence of a robust infrastructure for seed dispersion, such as seed markets and sectors. Crops biofortified with Zn or Fe are similar in appearance to their non-biofortified counterparts, whereas crops lacking provitamin A are clearly differentiated. HarvestPlus and its different non-governmental organization (NGO) companions provided OSP (Other Service Provider) to almost 24000 homes in LACs like Mozambique and Uganda between 2007 and 2009 (49) and several other African and Asian countries (Fig. 2). Although the pilot delivery project was unique to Uganda, it expanded upon 2 earlier CIP initiatives in Mozambique, eat orange and towards sustainable nutrition improvement. Planting supplies were sent through NGO partners since sweet potato vines were not sold in Uganda or Mozambique. While a team dedicated to effect evaluation conducted a randomized control study in parallel, an operations research component kept an eye on implementation activities. The 2 delivery strategies that were examined in the effect evaluation component were an intensive way that involved planting material delivery and training for two years and a mild method that involved planting material delivery and instruction for just 1 year. It was demonstrated that the less intense strategy was just as successful as the more intensive one and the experiment increased farm households' acceptance and consumption of orange sweet potatoes (OSP) in both nations. Consequently, the main target groups of this intervention, children and women, saw a twofold increase in their vitamin A intake.

### **Effectiveness of biological fortification**

The main source of proof for the efficacy of biological fortification is OSP. In both nations, the effectiveness was evaluated using a randomized controlled study. The aforementioned pilot delivery effort increased the likelihood of OSP adoption in Mozambique by 68% and in Uganda by 61% (50). Adoption of OSP led to a significant area under cultivation replacing other sweet potato varieties; in Mozambique and Uganda, the project raised the percentage of OSP in total sweet potato areas by 44% and 59% respectively. By the project's completion, vitamin A intake in Mozambique had

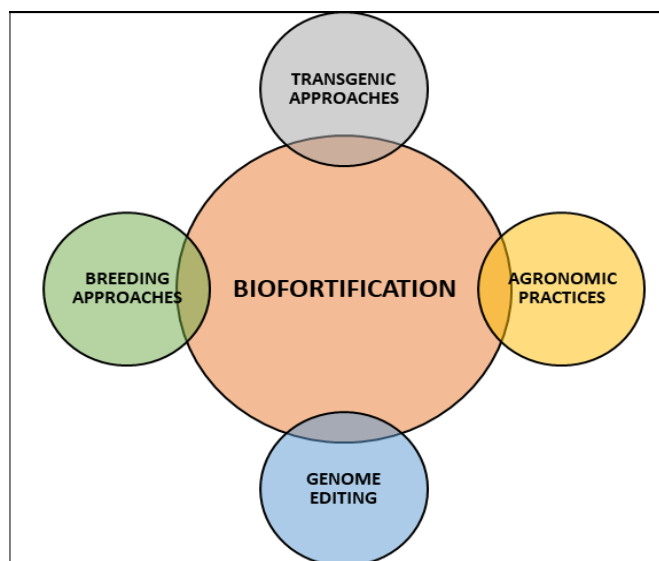


**Fig. 2.** Graph- biofortified varieties released in different regions.

doubled for each of the age/gender groups compared to baseline intakes; in Uganda, it had improved by nearly doubled for women and 2/3<sup>rd</sup> for older and younger children. In Uganda and Mozambique, OSP accounted for 52 % and 74 % of the total vitamin A consumption for children aged 6 to 35 months, which is the age group most concerned. As an outcome of the project, the substantial incidence of suboptimal vitamin A intake amongst a subset of breastfeeding children aged 12 to 35 months in Uganda decreased from almost 50 % to only 12 %. In children aged 5–7 who had reduced blood levels of vitamin A at the beginning of the study, researchers were additionally able to evaluate a slight but significant effect of eating OSP on their intake of vitamin A. Upon experiment completion, the researchers also discovered that women with a lower risk of marginal vitamin A deficiency were those who received higher vitamin A via OSP consumption.

### Challenges and future strategies for biofortification

Effective biofortification requires a combination of high yields, enhanced micronutrient density and widespread adoption by farmers and consumers. By 2030, HarvestPlus has identified 3 major challenges to overcome: increasing demand from consumers, integrating which are biofortified varieties into both private and public breeding programs and incorporating biological fortification into agricultural policies. The success of biological fortification efforts hinges on several key parameters, including the availability of genetic variation within breeding populations (Fig. 3), the reduction of antinutrients (such as polyphenols and phytate) and the enhancement of promoter compounds like ascorbic acid (vitamin C) and specific amino acids (methionine, lysine and cysteine), which facilitate the absorption of essential minerals. A critical objective in biofortification is not only to increase the concentration of micronutrients but also to enhance their biological availability. This can be achieved by decreasing antinutrients that hinder absorption while increasing compounds that promote mineral uptake. Postharvest processing also plays a crucial role, as significant nutrient losses can occur during milling, polishing and cooking (51). Therefore, strategies should focus on preserving micronutrient levels in edible seeds while ensuring that the nutrients remain bioavailable to consumers after food preparation (52). Additionally, the nutritional composition of harvested seeds can be significantly altered by environmental stressors. Micronutrients such as Fe and Zn function as antioxidants or essential cofactors in enzymatic processes, including electron transport and oxidation-reduction reactions. Consequently, they help protect cells from oxidative



**Fig. 3.** Various approaches to crop bio-fortification.

damage by scavenging reactive oxygen species (ROS) generated under environmental stress. Notably, biofortified crops with higher micronutrient concentrations have shown improved tolerance to harsh environmental conditions, making them more adaptable to climate variability.

### Conclusion

Biofortification represents a cost-effective and sustainable strategy for addressing micronutrient deficiencies, particularly in staple crops like wheat. This review highlights the identification of quantitative trait loci (QTLs) associated with Fe and Zn accumulation in wheat grains using molecular markers, providing valuable insights for breeding programs. The results underscore the potential of leveraging these genomic regions to develop nutrient-rich wheat varieties without compromising yield and agronomic performance. However, the accumulation of micronutrients in grains is influenced by genetic, environmental and soil-related factors, necessitating further research for successful implementation. To advance biofortification efforts, future research should prioritize validating identified QTLs across diverse wheat germplasm and multi-location trials to ensure their stability under different Agro-climatic conditions. Genome-wide association studies (GWAS) and fine mapping can further refine candidate gene identification, enabling precise genetic modifications. Integrating genomic selection (GS) and marker-

assisted selection (MAS) into conventional breeding programs will accelerate the development of high-yielding, nutrient-dense wheat varieties. Additionally, genome-editing technologies such as Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR Associated Protein 9 (CRISPR/Cas9) should be explored to enhance Fe and Zn uptake, transport and accumulation without negative trade-offs in yield and grain quality.

Beyond genetic advancements, agronomic and environmental strategies must also be considered. Research on soil amendments, beneficial microbial interactions and improved agricultural practices can complement genetic interventions by enhancing Fe and Zn biological availability in crops. Furthermore, human bioavailability studies are essential to determine how effectively increased micronutrient concentrations in wheat contribute to alleviating malnutrition. Considering the effect of climate change on soil nutrient dynamics and crop physiology, breeding strategies should also focus on improving resilience to stresses (abiotic) such as drought and heat. By integrating molecular breeding, advanced genomic tools and agronomic innovations, biofortified wheat has the potential to significantly contribute to global food security and nutrition. Future efforts should aim to bridge the gap between scientific advancements and practical applications by fostering collaboration between researchers, policymakers and agricultural stakeholders. Ensuring widespread adoption and accessibility of biologically fortified crops will be crucial in addressing micronutrient deficiencies at a global scale.

## Acknowledgements

The authors have contributed to this manuscript and a deep thankfulness is offered for the support of this article. Fundings are not arranged by any personal sources; we are thankful to Lovely Professional University for it.

## Authors' contributions

DP and AKS have written this manuscript and contributed majorly to it. JY, NG, BY, RK, AK, AY and SS have contributed to reviewing the manuscript. BY and RK designed the entire idea for making a review paper, contributed to writing, reviewing and correcting. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** The authors do not have any conflicts of interest to declare.

**Ethical issues:** None

## References

- Von Grebmer K, Saltzman A, Birol E, Wiesman D, Prasai N, Yin S, et al. Synopsis: 2014 global hunger index: The challenge of hidden hunger. Washington, DC: Intl Food Policy Res Inst; 2014. (Vol. 83). <https://doi.org/10.2499/9780896299580>
- Vlaic RA, Mureşan CC, Muste S, Mureşan V, Pop A, Mureşan GPA. *Boletus edulis* mushroom flour-based wheat bread as innovative fortified bakery product. Bull UASVM Food Sci Technol. 2019;76(1):52–62. <https://doi.org/10.15835/buasvmcn-fst:2018.0022>
- Velu G, Crespo Herrera L, Guzman C, Huerta J, Payne T, Singh RP. Assessing genetic diversity to breed competitive biofortified wheat with enhanced grain Zn and Fe concentrations. Front Plant Sci. 2019;9:1971. <https://doi.org/10.3389/fpls.2018.01971>
- Kromann P, Valverde F, Alvarado S, Vélez R, Pisuña J, Potosí B, et al. Can Andean potatoes be agronomically biofortified with iron and zinc fertilizers? Plant Soil. 2017;411(1-2):1–18. <https://doi.org/10.1007/s11104-016-3065-0>
- Buturi CV, Mauro RP, Fogliano V, Leonardi C, Giuffrida F. Mineral biofortification of vegetables as a tool to improve human diet. Foods. 2021;10(2):223. <https://doi.org/10.3390/foods10020223>
- De Souza JZ, De Mello Prado R, Silva SL, Farias TP, Neto JG, Junior JS. Silicon leaf fertilization promotes biofortification and increases dry matter, ascorbate content, and decreases post-harvest leaf water loss of chard and kale. Commun Soil Sci Plant Anal. 2019;50(2):1–9. <https://doi.org/10.1080/00103624.2018.1556288>
- Timpanaro G, Bellia C, Foti VT, Scuderi A. Consumer behaviour of purchasing biofortified food products. Sustainability. 2020;12(16):6297. <https://doi.org/10.3390/su12166297>
- HarvestPlus. Disseminating orange-fleshed sweet potato: Findings from a HarvestPlus project in Mozambique and Uganda. Washington, DC: HarvestPlus; 2010.
- White PJ, Broadley MR. Biofortifying crops with essential mineral elements. Trends Plant Sci. 2005;10(12):586–93. <https://doi.org/10.1016/j.tplants.2005.10.001>
- Siwela M, Pillay K, Govender L, Lottering S, Mudau FN, Modi AT, et al. Biofortified crops for combating hidden hunger in South Africa: Availability, acceptability, micronutrient retention and bioavailability. Foods. 2020;9(6):815. <https://doi.org/10.3390/foods9060815>
- Tang T, Xie H, Wang Y, Lü B, Liang J. The effect of sucrose and abscisic acid interaction on sucrose synthase and its relationship to grain filling of rice (*Oryza sativa* L.). J Exp Bot. 2009;60(9):2641–52. <https://doi.org/10.1093/jxb/erp114>
- Fanzo J, Bellows AL, Spiker ML, Thorne-Lyman AL, Bloem MW. The importance of food systems and the environment for nutrition. Am J Clin Nutr. 2021;113(1):7–16. <https://doi.org/10.1093/ajcn/nqaa313>
- Obrador A, Gonzalez D, Alvarez JM. Effect of inorganic and organic copper fertilizers on copper nutrition in *Spinacia oleracea* and on labile copper in soil. J Agric Food Chem. 2013;61(20):4692–701. <https://doi.org/10.1021/jf305473f>
- Waters BM, Grusak MA. Quantitative trait locus mapping for seed mineral concentrations in two *Arabidopsis thaliana* recombinant inbred populations. New Phytol. 2008;179(4):1033–47. <https://doi.org/10.1111/j.1469-8137.2008.02544.x>
- Chavez AL, Sánchez T, Jaramillo G, Bedoya JM, Echeverry J, Bolaños EA, et al. Variation of quality traits in cassava roots evaluated in landraces and improved clones. Euphytica. 2005;143(1):125–33. <https://doi.org/10.1007/s10681-005-3057-2>
- Bouis HE, Hotz C, McClafferty B, Meenakshi JV, Pfeiffer WH. Biofortification: A new tool to reduce micronutrient malnutrition. Food Nutr Bull. 2011;32(Suppl 1):S31–40. <https://doi.org/10.1177/15648265110321S105>
- Bouis HE, Saltzman A. Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through. Glob Food Secur. 2017;12:49–58. <https://doi.org/10.1016/j.gfs.2017.01.009>
- Bouis HE, Welch RM. Biofortification: A sustainable agricultural strategy for reducing micronutrient malnutrition in the Global South. Crop Sci. 2010;50:20–32. <https://doi.org/10.2135/cropsci2009.09.0531>
- Pérez-Massot E, Banakar R, Gómez-Galera S, Zorrilla-López U, Sanahuja G, Arjón G, et al. The contribution of transgenic plants to better health through improved nutrition: Opportunities and constraints. Genes Nutr. 2013;8:29–41. <https://doi.org/10.1007/s12263-012-0315-5>
- Christou P, Twyman RM. The potential of genetically enhanced

- plants to address food insecurity. *Nutr Res Rev.* 2004;17(1):23–42. <https://doi.org/10.1079/NRR200373>
21. Kenz M, Stangoulis JCR. Calcium biofortification of crops - Challenges and projected benefits. *Front Plant Sci.* 2021;12. <https://doi.org/10.3389/fpls.2021.669053>
  22. Siddique KH, Li X, Gruber K. Rediscovering Asia's forgotten crops to fight chronic and hidden hunger. *Nat Plants.* 2021;7(2):116-22. <https://doi.org/10.1038/s41477-021-00850-z>
  23. da Silva DF, Cipriano PE, de Souza RR, Júnior MS, da Silva RF, Faquin V, et al. Anatomical and physiological characteristics of *Raphanus sativus* L. submitted to different selenium sources and forms application. *Sci Hortic.* 2020;260:108839. <https://doi.org/10.1016/j.scienta.2019.108839>
  24. Barrameda-Medina Y, Leon MBB, Lentini M, Esposito S, Baenas N, Moreno DA, et al. Biofortification improves phytochemicals and amino-acidic profile in *Brassica oleracea* cv Bronco. *Plant Sci.* 2017;258:45-51. <https://doi.org/10.1016/j.plantsci.2017.02.004>
  25. Pingali P, Sunder N. Transitioning toward nutrition-sensitive food systems in developing countries. *Annu Rev Resour Econ.* 2017;9:439-59. <https://doi.org/10.1146/annurev-resource-100516-053552>
  26. D'Imperio M, Renna M, Cardinali A, Buttarò D, Serio F, Santamaria P. Biofortification and bioaccessibility in soilless "baby leaf" vegetable production. *Food Chem.* 2016;213:149-56. <https://doi.org/10.1016/j.foodchem.2016.06.071>
  27. International Food Policy Research Institute. Analysis of CGIAR 2018 policy contributions: Overview and country-level insights. <https://www.ifpri.org/publication/analysis-cgiar-2018-policy-contributions-overview-and-country-level-insights>
  28. Liang J, Li Z, Tsuji K, Nakano K, Nout MR, Hamer RJ. Milling characteristics and distribution of phytic acid and zinc in long-, medium- and short-grain rice. *J Cereal Sci.* 2008;48(1):83-91. <https://doi.org/10.1016/j.jcs.2007.08.003>
  29. Calayugan MIC, Swamy BM, Nha CT, Palanog AD, Biswas PS, Descalsota-Empleo GIL, et al. Zinc-biofortified rice: a sustainable food-based product for fighting zinc malnutrition. In: *Rice improvement: physiological, molecular breeding and genetic perspectives.* Cham: Springer; 2021. p. 449-70. [https://doi.org/10.1007/978-3-030-66530-2\\_13](https://doi.org/10.1007/978-3-030-66530-2_13)
  30. De Sousa Lima F, Nascimento CWA, Da Silva Sousa C. Zinc fertilization as an alternative to increase the concentration of micronutrients in edible parts of vegetables. *Rev Bras Cienc Agrar.* 2015;10(3):403-8. <https://doi.org/10.5039/agraria.v10i3a5132>
  31. McDowell LR. Minerals in animal and human nutrition. 2nd ed. Amsterdam: Elsevier Science BV; 2003. <https://doi.org/10.1016/B978-0-444-51367-0.X5001-6>
  32. Natesan S, Duraisamy T, Pukalenthay B, Chandran S, Nallathambi J, Adhimoalam K, et al. Enhancing  $\beta$ -carotene concentration in parental lines of CO6 maize hybrid through marker-assisted backcross breeding (MABB). *Front Nutr.* 2020;7:134. <https://doi.org/10.3389/fnut.2020.00134>
  33. Kyriacou MC, Roupheal Y. Towards a new definition of quality for fresh fruits and vegetables. *Sci Hortic.* 2018;234:463-9. <https://doi.org/10.1016/j.scienta.2017.09.046>
  34. Hurrell RM. Factors associated with regular exercise. *Percept Mot Skills.* 1997;84(3):871-4. <https://doi.org/10.2466/pms.1997.84.3.871>
  35. Roohani N, Hurrell R, Kelishadi R, Schulin R. Zinc and its importance for human health: An integrative review. *J Res Med Sci.* 2013;18(2):144.
  36. Al-Babili S, Beyer P. Golden Rice-five years on the road-five years to go. *Trends Plant Sci.* 2005;10(12):565-73. <https://doi.org/10.1016/j.tplants.2005.10.006>
  37. Skeaff SA. Iodine deficiency in pregnancy: The effect on neurodevelopment in the child. *Nutrients.* 2011;3(2):265-73. <https://doi.org/10.3390/nu3020265>
  38. De Valença AW, Bake A, Brouwer ID, Giller KE. Agronomic biofortification of crops to fight hidden hunger in sub-Saharan Africa. *Glob Food Secur.* 2017;12:8-14. <https://doi.org/10.1016/j.gfs.2016.12.001>
  39. Saltzman A, Birol E, Bouis HE, Boy E, De Moura FF, Islam Y, et al. Biofortification: Progress toward a more nourishing future. *Glob Food Secur.* 2013;2(1):9-17. <https://doi.org/10.1016/j.gfs.2012.12.003>
  40. Diretto G, Tavazza R, Welsch R, Pizzichini D, Mourgues F, Papacchioli V, et al. Metabolic engineering of potato tuber carotenoids through tuber-specific silencing of lycopene epsilon cyclase. *BMC Plant Biol.* 2006;6:1-11. <https://doi.org/10.1186/1471-2229-6-13>
  41. Batis C, Marron-Ponce JA, Stern D, Vandevijvere S, Barquera S, Rivera JA. Adoption of healthy and sustainable diets in Mexico does not imply higher expenditure on food. *Nat Food.* 2021;2(10):792-801. <https://doi.org/10.1038/s43016-021-00359-w>
  42. Bouis HE, Saltzman A, Birol E. Improving nutrition through biofortification. *Agric Impro Nutr Seizing Momentum.* 2019;47. <https://doi.org/10.1079/9781786399311.0047>
  43. Juliano BO. Factors affecting nutritional properties of rice protein. *Trans Natl Acad Sci Technol.* 1985;7:205-16.
  44. van Ginkel M, Cherfas J. What is wrong with biofortification. *Glob Food Secur.* 2023;37:100689. <https://doi.org/10.1016/j.gfs.2023.100689>
  45. Buturi CV, Leonardi VFC, Giuffrida F. Mineral biofortification of vegetables as a tool to improve human diet. *Foods.* 2021;10(2):223. <https://doi.org/10.3390/foods10020223>
  46. Castillo-Godina RG, Foroughbakhch-Pournavab R, Benavides-Mendoza A. Effect of selenium on elemental concentration and antioxidant enzymatic activity of tomato plants. *J Agric Sci Technol.* 2016;18:233-44.
  47. White PJ, Broadley MR. Biofortification of crops with seven mineral elements often lacking in human diets: Iron, zinc, copper, calcium, magnesium, selenium and iodine. *New Phytol.* 2009;182(1):49-84. <https://doi.org/10.1111/j.1469-8137.2008.02738.x>
  48. Montesano FF, D'Imperio M, Parente A, Cardinali A, Renna M, Serio F. Green bean biofortification for Si through soilless cultivation: Plant response and Si bioaccessibility in pods. *Sci Rep.* 2016;6:1-9. <https://doi.org/10.1038/srep31662>
  49. Haas D, Défago G. Biological control of soil-borne pathogens by fluorescent pseudomonads. *Nat Rev Microbiol.* 2005;3(4):307-19. <https://doi.org/10.1038/nrmicro1129>
  50. HarvestPlus. Biofortification: the evidence. A summary of research informing scaling up of biofortification to improve nutrition and health globally. Washington, DC: HarvestPlus; 2019.
  51. Gómez-Galera S, Rojas E, Sudhakar D, Zhu C, Pelacho AM, Capell T, et al. Critical evaluation of strategies for mineral fortification of staple food crops. *Transgenic Res.* 2010;19:165-80. <https://doi.org/10.1007/s11248-009-9311-y>
  52. Gregorio GB, Senadhira D, Htut H, Graham RD. Breeding for trace mineral density in rice. *Food Nutr Bull.* 2000;21(4):382-6. <https://doi.org/10.1177/156482650002100407>

**Additional information**

**Peer review:** Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

**Reprints & permissions information** is available at [https://horizonpublishing.com/journals/index.php/PST/open\\_access\\_policy](https://horizonpublishing.com/journals/index.php/PST/open_access_policy)

**Publisher's Note:** Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Indexing:** Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc

See [https://horizonpublishing.com/journals/index.php/PST/indexing\\_abstracting](https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting)

**Copyright:** © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

**Publisher information:** Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.