Brazilian Journal of Biology®

ISSN 1519-6984 (Print)
ISSN 1678-4375 (Online)

Original Article

Photosynthetic modification of plants through recent technologies: a valuable way to ensure crop fortification

Modificação fotossintética de plantas por meio de tecnologias recentes: uma forma valiosa de garantir a fortificação das culturas

F. O. Areche[a*], J. M. M. López[b], C. M. C. Mamani[c], M. N. M. Alberto[d], V. G. S. Araujo[a], P. A. P. Pastrana[a], B. F. Camayo-Lapa[e], M. A. Quispe-Solano[e], J. Y. Saldarriaga[f], C. P. E. Ayre[a], S. M. Carrasco[g], A. V. Roman[g], D. D. C. Flores[a] and D. D. Cruz Nieto[h]

[a]National University of Huancavelica, Huancavelica, Peru
[b]Santiago Antúnez of Mayolo National University, Huaraz, Peru
[c]National University of Jaen, Jaen, Peru
[d]National University of Cañete, Cañete, Peru
[e]National University of Central Peru, Huancayo, Peru
[f]Santiago Antunez of Mayolo National University, Huaraz, Peru
[g]Micaela Bastidas National University of Apurimac, Abancay, Peru
[h]José Faustino Sánchez Carrión National University, Huacho, Peru

Abstract

The 2030 Sustainable Development Goals of the United Nations include a strong emphasis on ending hunger worldwide. According to the 2019 Global Food Security Index, while 88% of countries claim there is sufficient food supply in their country, the sad reality is that 1 in 3 countries is facing insufficient availability of food supply, which means that in those countries, more than 10% of the population is malnourished. Since nutrition is crucial to leading a healthy life and satisfying food security needs, several governments have turned to national nutrition surveys to gauge the extent of malnutrition in their populations. Plants are able to grow, develop, and store nutrients by photosynthesis, which convert light into chemical energy through cell redox regulatory networks. A photosynthesis system's electron flow may be adjusted to accommodate varying light and environmental circumstances. Many techniques exist for controlling the flow of electrons emitted during light processes in order to save or waste energy. The two protein molecules TROL and flavoenzyme ferredoxin (oxidoreductase+NADP) (FNR) interact dynamically to form an excellent molecular switch capable of splitting electrons from the photosystem. The TROL-FNR bifurcation may be limited by either generating NADPH or preventing reactive oxygen species from propagating. TROL-based genome editing is an experimental method for enhancing plant stress and defensive responses, efficiency, and ultimately agricultural production.

Keywords: photosynthetic processes, fortification, technologies, crop yield.

Resumo

Os Objetivos de Desenvolvimento Sustentável de 2030 da Organização das Nações Unidas incluem uma forte ênfase em acabar com a fome em todo o mundo. De acordo com o Índice Global de Segurança Alimentar de 2019, enquanto 88% dos países afirmam que há abastecimento alimentar suficiente em seu país, a triste realidade é que 1 em cada 3 países enfrenta disponibilidade insuficiente de alimentos, o que significa que, nesses países, mais de 10% da população está desnutrida. Uma vez que a nutrição é crucial para levar uma vida saudável e satisfazer as necessidades de segurança alimentar, vários governos recorreram a pesquisas nacionais de nutrição para avaliar a extensão da desnutrição em suas populações. As plantas são capazes de crescer, desenvolver e armazenar nutrientes pela fotossíntese, que converte luz em energia química por meio de redes reguladoras redox celulares. O fluxo de elétrons de um sistema de fotossíntese pode ser ajustado para acomodar luz variável e circunstâncias ambientais. Existem muitas técnicas para controlar o fluxo de elétrons emitidos durante os processos de luz, a fim de economizar ou desperdiçar energia. As duas moléculas de proteína TROL e a flavoenzima ferredoxina (oxidorredutase+NADP) (FNR) interagem dinamicamente para formar um excelente interruptor molecular capaz de separar elétrons do fotossistema. A bifurcação TROL-FNR pode ser limitada, gerando NADPH ou impedindo a propagação de espécies reativas de oxigênio. A edição do genoma baseada em TROL é um método experimental para aumentar o estresse da planta, as respostas defensivas, a eficiência e, finalmente, a produção agrícola.

Palavras-chave: processos fotossintéticos, fortificação, tecnologias, rendimento da colheita.

*e-mail: franklin.ore@unh.edu.pe
Received: February 6, 2023 – Accepted: April 23, 2023

1. Introduction

The growth in agricultural output over the last 70 years has been sufficient to fulfil the needs of the whole world (Pestisha et al., 2023). Recent years have seen a stagnation in the yields of some critical food crops, despite the fact that these improvements were mostly the result of the breeding of better yielding varieties and breakthroughs in agronomic practices (Jain et al., 2023). There will likely be more than 9 billion people on Earth by 2050. Creating new crop types with increased yields is essential to keeping up with the rising demand for food and fuel. Wheat, soybean (*Glycine max*), and maize (*Zea mays*) production increases of 70% to 100% are needed to satisfy these demands. One option, clearing land for food production, has the major problem of inflicting environmental harm to unique ecosystems, ultimately leading to a worldwide loss in biodiversity. Increasing arable land also increases greenhouse gas emissions and harms marine and freshwater ecosystems due to the use of fertilisers and pesticides. It will be required to supply global food needs without expanding the quantity of cultivable land in order to limit the negative effects on the environment (Banerjee et al., 2023; Jiang et al., 2022; Gondal, 2023; Gondal et al., 2021a, b). The creation of new types of important crops is crucial in order to boost yields without negatively impacting the environment. This might be achieved by using genetic engineering to boost photosynthesis. Better crop nutrition is essential, in addition to improving yields. While the output of staple crops high in calories has expanded thanks to new crop types over the last 50 years, the production of non-staple crops rich in micronutrients has not. Fruits, vegetables, and other key animal products, which are high in micronutrients, have seen their costs rise, putting them out of reach for many people living in poverty. More than two billion individuals throughout the world suffer from vitamin deficiencies. Inadequate vitamin and mineral intake lead directly to micronutrient deficits. It is possible to increase the bioavailability of essential nutrients in modern crops by a process called biofortification.

2. Role and mechanism of TROL and flavoenzyme ferredoxin in biofortification

One of the most critical steps in photosynthesis is the creation of NADPH by ferredoxin FNR; a flavoenzyme in plants (Mulo, 2011) and in this enzymatic process, one molecule of NADPH requires two molecules of reduced ferredoxin (Fd). In the cell and the chloroplast stroma, NADPH is used in several metabolic processes (Scheibe and Dietz, 2012). It is only in the presence of light that ferredoxin and NADPH undergo electron cycling. While in the dark reaction and in non-photosynthesis species, the FNR predominantly functions in opposite, using NADPH to give condensed ferredoxin for numerous metabolic paths, such as nitrogen fixation, sulfur-iron protein biogenesis, oxidative stress response, steroid metabolism and terpenoids biosynthesis and when it comes to photosynthesis and overall plant metabolism, FNR is a key component (Aliverti et al., 2008). In iron-sulfur protein known as the electron donor, Fd, is both a bottleneck and a hub for the movement of electrons from the photosystem I or PSI. Proposed mechanisms for FNR binding to vascular plants thylakoid membranes include the cytochrome B6/f complex, PSI-E component, and in a NADPH dehydrogenase complex (Zhang et al., 2001). In any of these studies, FNR-binding protein association domains have not been found. The link between FNR and in species other than vascular plants, photosynthetic membranes have just lately been identified (Pini et al., 2019). According to a number of noteworthy studies, the distribution of FNR between solubilized and thylakoid-bound forms has a substantial effect on photosynthetic regulation, FAD cofactor association, photo-oxidative stress resistant, Fd-FNR interactions, oxidative stress resistant and FNR catalytic properties (Onda and Hase, 2004). Transgenic plants that overexpress chloroplast FNR are especially noteworthy for their capacity to survive oxidative stress and sustain normal photosynthesis. In addition, photo-oxidative damage is more likely to harm, FNR knock-down plants because of their curtailed development and reduced photosynthetic activity (Lintala et al., 2012). Methylene viologen is required for the regulation of FNR from thylakoid membranes, which is perhaps the most exciting result. Finally, no binding of FNR to thylakoid proteins was seen in tic62trol double mutants (Lintala et al., 2014).

Chloroplastic FNR may have additional activities and physiological purposes in vascular plants, according to a new theory (Goss and Hanke, 2014). FNR binding and release from Tic62 are the foundations of these hypotheses (Lintala et al., 2014). To begin with the chloroplast inner envelope translocation mechanism was found to include Tic62 (a 62kDa translocon), however Tic62 has now been related to at least 2 different partitions, photosynthetic membranes of the chloroplasts and the chloroplast stroma. FNR binding was shown to be vital in many of the Tic62 family members, however not all of them had numerous repeats of the critical protein region seen in Tic62 (Balsera et al., 2007). The C-terminus of TROL was also revealed to have a similar pattern. Membrane recruitment motif (MRM) is the name given to the domain that has the greatest affinity for FNR. Using Tic62 as a model, it was hypothesized that the interaction was light and pH-dependent (but not proven). Thylakoid-localized FNR is thought to be primarily attached to the membrane through two interaction partners, TROL, and Tic62 according to Benz et al. (2010). By contrast, the researchers say that the thylakoid pool is more focused on other functions than photosynthesis. Light and redox conditions may influence the distribution of FNR. For the benefit of electron transport through numerous Fd-dependent pathways, FNR is retained at membrane surfaces throughout the night and early morning. An appropriate metabolic response to environmental stimuli would be ensured in this circumstance.

It has yet to be determined where soluble Tic62 attaches to thylakoids because MRM is not present in all plant species. Despite this, TROL is an integral membrane protein with two distinct localizations (Vojta et al., 2018). Thylakoid membranes contain it in its mature form, whereas the inner chloroplast envelope has it in its precursor form. The data indicates that TROL is located near PSI in previously unknown thylakoid regions. TROL sequences from vascular plants have been shown to include FNR MRM in every case.

There is further evidence to suggest that the TROL MRM has better affinity for binding FNR by many orders of magnitude than the Tic62 MRM. It is possible that Arabidopsis' dynamic supramolecular complex, which has a molecular mass of 190 kDa, contains TROL that is connected with FNR.

The putative active region of TROL's lumen-located rhodanases-like domain (RHO) has an aspartate residue rather than the conserved cysteine, indicating that it is not involved in sulphate detoxification (Jurić et al., 2009). Cell-division-cycle (CDC25) phosphatase RHO domains have structural resemblance with the catalytic domain of RHO domains. Inactive RHO domains have been found to interact with quinolinediones, which have been linked to redox sensing (Brisson et al., 2005). There have been two recent studies on plant sulphur transferases and rhodanases (Selles et al., 2019). Alternate mechanisms for FNR binding and TROL release through RHO domain redox sensing have recently been suggested (Vojta and Fulgosi, 2019). RHO may detect luminal (redox) signals and transmit them across the thylakoid membrane, leading to distinction FNR stromal side binding, according to this concept (Vojta and Fulgosi, 2012). It has also been suggested that a TROL proline-rich region, known as PEPE (Jurić et al., 2009), may have a role in the MRM. Allowing the free mobility of bound FNR or alternative linkages with other supramolecular complexes and membrane domains, proline residues in PEPE may operate as molecules. As a result of FNR's dynamic recruitment, electron allocation and/or the preference for Fd-dependent pathways may be altered. Chloroplasts from Arabidopsis trol mutant plants generate much less superoxide anion radicals than those from wild-type (WT) plants. This decrease may be seen in trol chloroplasts that have been exposed to both dark and growth light conditions to acclimatize themselves. Astonishingly, trol chloroplasts generate roughly 40% less superoxide anion radicals even when exposed to ROS-producing methyl viologen (a pesticide derived from paraquat). According to previous research, it's possible that FNR can effectively remove superoxide anion, or that electrons are distributed in ways other than the LET. When the TROL-FNR link is formed, despite the fact that LET is favoured, statistics reveal that LET is preferred only when the TROL-FNR relationship is established. Alternatives to TROL include sinks downstream of the PSI donor point where electrons may flow quickly without TROL. FNR's dynamic recruitment to thylakoids is completely halted in the absence of light- or pH-dependent dynamic recruitment by TROL. TROL-FNR interactions and FNR-photosynthetic membrane contacts in vascular plants seem to have a substantial association.

Crop improvement might be facilitated by modifying the TROL-FNR interaction itself, or by altering reactions and pathways upstream and downwind. Genome engineering might be used to alter TROL's FNR-binding or regulatory domains, for instance. For example, FNR enzymes may be transferred from C4 plants to C3 plants or the other way around. In comparison to the C3 FNR, the C4 FNR has a much greater affinity for the TROL ITEP domain (Rac and Fulgosi, 2019). In order to enhance photosynthetic efficiency, a rise in TROL levels must be accompanied by an improvement in reduced ferredoxin availability and the system's capacity to produce the required reduction equivalents. If the synthesis of reduction equivalents is altered, the redox equilibrium of chloroplasts may be disrupted instead of benefiting plants.

It is crucial that TROL-FNR dynamic interaction be taken into consideration. in the concept of FNR recruitment to the photosynthetic membrane. An important method for controlling and prioritizing energy-saving and energy-dissipating activities in vascular plant photosynthesis has been proposed by this work. Genome editing of agriculturally essential species might result in more stress-resistant crops if TROL and FNR cooperate.

3. Relationship between photosynthesis and yield

Everything we eat on Earth has its origins in photosynthesis, either directly in the growth of plants or indirectly through the food chain. In addition, oil, which originated from photosynthates, now accounts for as much as 90% of the world's energy production. Figure 1 explains the short mechanism of photosynthesis system I and II. The fundamental determinant of harvest yield is the cumulative rate of photosynthesis during the growing season. A crucial factor is the pace at which light is A, gathered, and B, turned into fruit (i.e., biomass or grain). The Calvin-Benson cycle (CBC) and photorespiration are two pathways by which plants absorb carbon dioxide (CO_2). The complex stromal enzyme rubisco is important to these processes. It's the primary protein and nitrogen source in plant tissues, and it's responsible for synthesising over half of the protein in leaves. The photosynthetic enzyme rubisco has been studied intensively because of its potential as a genetic engineering target. Increasing photosynthesis, electron transport, and photorespiration is widely acknowledged as a key strategy for increasing crop yields. In their recent extensive review, Simkin et al. (2019) briefly highlighted this option. This essay will explore how a multi-target strategy for boosting photosynthesis in GMO crops might affect their nutritional density.

4. Genetic engineering in crop fortification

It is possible to breed new varieties of plants with certain desired characteristics using genetic engineering techniques. Evolutionary and taxonomically diverse organisms may share genes in order to facilitate the transmission and expression of desired features. Furthermore, transgenic techniques are the sole viable alternative for fortifying crops with a particular micronutrient when said vitamin is not naturally generated in said crops (Perez-Massot et al., 2013). Various methods have been used to create transgenic crops, including the introduction of new genes, overexpression of existing genes, downregulation of expression, and disruption of inhibitor synthesis pathway genes. Figure 2 clearly explain genetically modified and un modified plants show different growth.

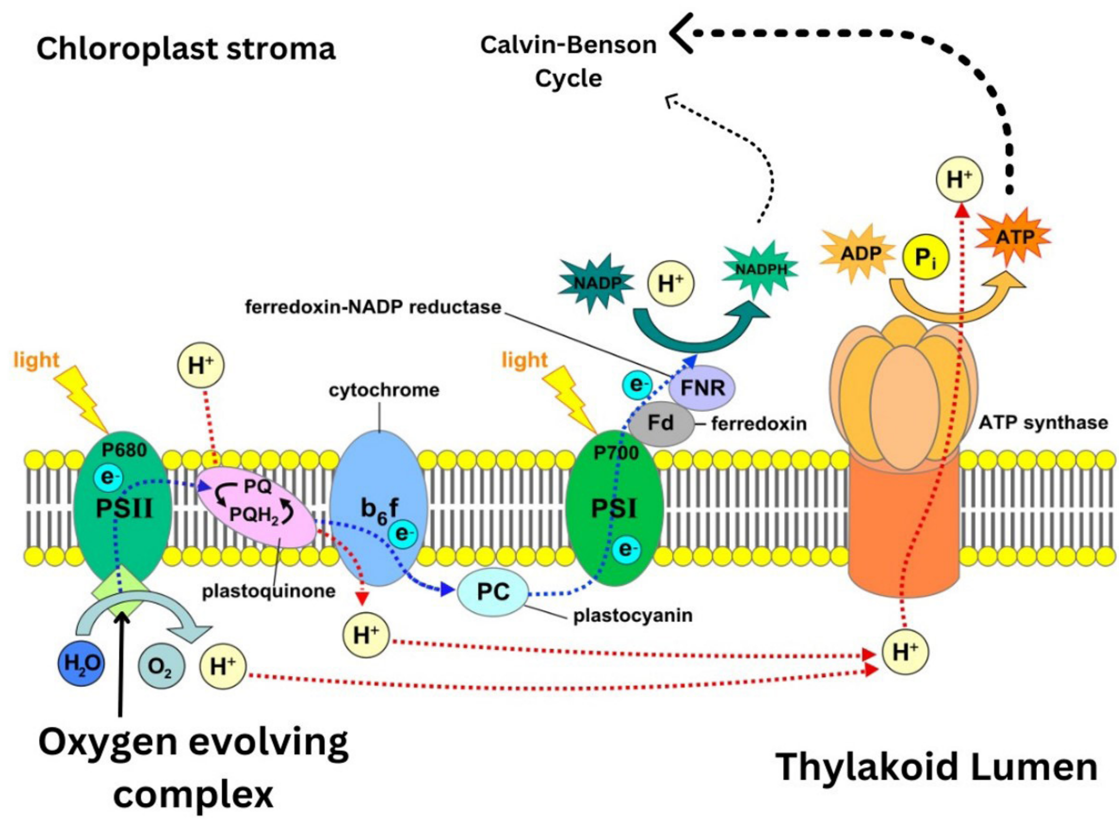

Figure 1. Photosynthetic mechanism of PS1 and PSII.

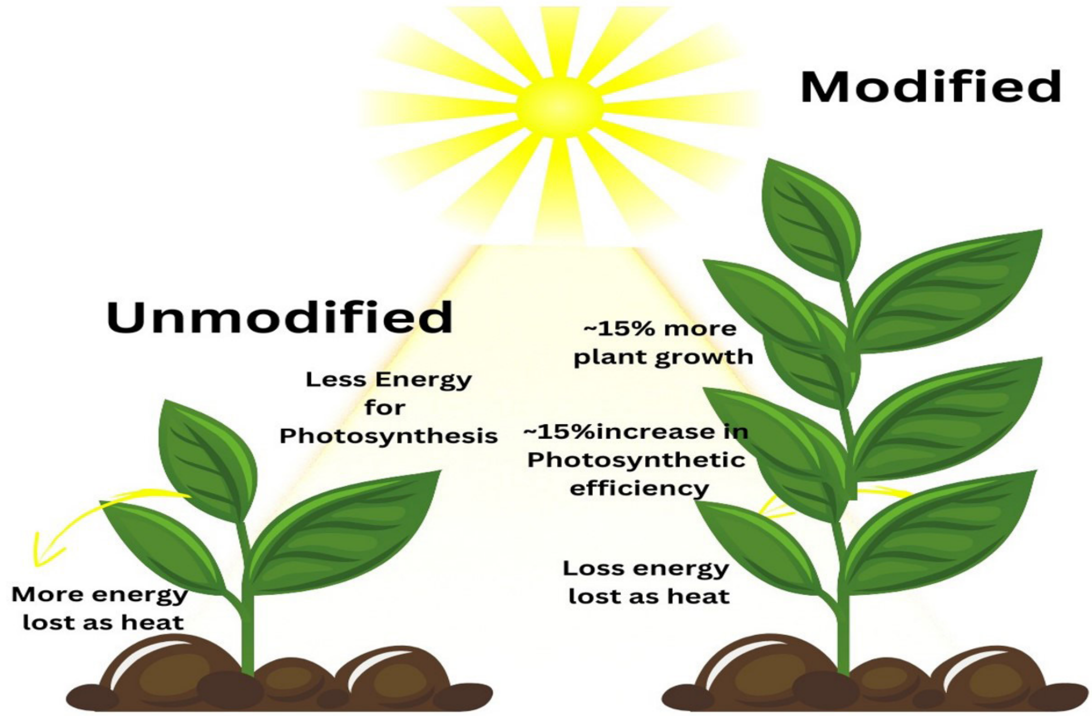

Figure 2. A general comparison of genetically modified and un modified plants.

5. Multi targeted approaches

Over-expression studies of CBC proteins, photorespiratory proteins, and proteins that increase photosynthetic electron transport have been conducted lately. These findings point to the possibility of a target- and plant-specific synergistic impact of numerous target manipulations on biomass accumulation. These results also show that it is important to investigate the possibility of targeting other routes. Significant production gains have been seen in both laboratory and field settings thanks to a combination of CBC and photorespiration or CBC plus electron transport. However, at the moment ETC targeting is mostly concerned with influencing one specific target. Targeting the cyt b6f complex, plastocyanin, and ferrodoxin in tandem has the ability to either boost electron transport or maintain consistently high rates throughout a wide variety of environmental circumstances. The next stage in enhancing crop CO2 absorption rates is to simultaneously target CBC, ETC, and Photorespiration.

Current efforts to enhance photosynthesis in order to boost crop yields are concentrated on leaf tissue, while the role of photosynthesis in non-foliar green tissues has received comparatively less attention. Simkin et al. (2007) have synthesized the existing research to assess the impact of various photosynthetically active organs on yield and quality of fruits and grains. It has been proposed that photosynthesis in non-leafy plant tissues, such as maize husks, wheat ear husks, and petioles and stems, may offer an alternate supply of photoassimilates necessary for optimum yields and quality. Transgenic wheat with elevated SBPase activity was shown by Simkin et al. (2008) to have enhanced gross photosynthesis in the ears of transgenic lines compared to natural type. The authors also suggested that the reported 40% increase in grain production in SBPase OE wheat may not have been primarily attributable to foliar expression, but rather that enhanced activity in the ears may have contributed to this result. This research has brought to light the advantages of regulating non-foliar photosynthesis and its potential influence on quality and nutritional value (i.e., in fruit, wheat ears, seeds, and embryos).

Therefore, depending on the role of non-foliar tissue in photosynthetic assimilation and (ii) the species-species interaction of multiple transgenes on cumulative yield, a multi-gene, multi-tissue targeting approach to increasing photosynthetic efficiencies in crops may increase the availability of photoassimilates for growth. As a result, further study is needed into the impact of non-foliar photosynthesis on production and quality in these extractable locations. Since photosynthesis is responsible for producing a large number of vitamin precursors, it may be possible to alter the nutritional value of fruits, grains, and leaves by tinkering with photosynthesis.

6. Gene editing in crop fortification

Zinc-finger nucleases (ZFNs) and Transcription activator-like effector nucleases (TALENs) are two examples of the mega-nucleases that have revolutionized gene editing. When compared to traditional DNA transfer methods like Agrobacterium-mediated transfer or particle bombardment, the specificity of these enzymes—which consist of DNA binding domains paired with nuclease domains for producing DNA breakages at specified positions—is striking. Tobacco, Arabidopsis, rice, wheat, and barley are only some of the plants that have benefited from their usage in genetic engineering. However, creating these proteins is difficult, which makes it costly and time-consuming.

However, the Crispr-Cas9 technology may address the problem of employing these mega-nucleases by providing a more accurate, cost-effective, and adaptable alternative. It requires the determination of cleavage sites by the use of guide RNAs that are unique to a certain sequence and a PAM motif. However, sometimes cleavage develops in the wrong place, leading to unintended consequences. The lengthening of the PAM sequence has prevented these unintended cuts. Crispr-cas technology provides the ability to generate transgenics without requiring transformation and tissue culture plants by altering the germline cells. The same is true of the possibility for engineering single cells with this technique, however regenerating such cells remains challenging. Using these methods, many biofortified transgenic crops have been created, including rice, wheat, and Arabidopsis, which are all enriched with iron, zinc, vitamins A and B1, and other essential micronutrients. Small RNA processing gene mutant lines were created in Glycine max and Medicago truncatula utilizing CRISPR/Cas9 and TALENs. Similarly, CRISPR/Cas9 was used to effectively inhibit the activation of a gene involved in symbiotic nitrogen fixation in cowpeas. Targeting the Osor gene using CRISPR/Cas9 in rice increases the amount of calli -carotene. CRISPR-Cas9 was recently used to introduce a 5.2 kb cassette of carotenoid biosynthesis into marker-free rice, resulting in a strain with a much higher concentration of these beneficial pigments (Dong et al., 2020). These genome editing techniques offer the potential to rapidly and cheaply generate a wide variety of transgenics.

7. Biofortification through agronomic approaches

Agriculture provides the majority of the world's population, especially those living in poorer nations, with the majority of their daily nutritional needs (Graham et al., 2001; Javed et al., 2021). Cereals including wheat, maize, rice, and cassava are staples in the diets of most people across the world. Several vitamins and minerals are not abundant in these. The micronutrient content of staple crops may be improved by agronomic biofortification. It is common practice to use micronutrients as fertilisers in order to boost the plant's ability to absorb them. In addition, several plant metabolic activities need the presence of certain micronutrients in the plant's diet.

Some of the agricultural methods that have been put into place thus far include: irrigation, sophisticated tillage equipment, and soil amendments (Ahmad et al., 2017; Ch et al., 2021; Husnain et al., 2021; Tayyiba et al., 2021; Gondal et al., 2022; Gondal and Tayyiba, 2022). In order to break down the organic material in the soil, the plant must secrete enzymes and organic acids.

In addition, it secretes signaling molecules like flavonoids that attract beneficial microorganisms that help in nutrition absorption and give protection from abiotic and biotic stressors (Lyu and Wehby, 2020). Plants may benefit from the release of hormones, antibiotics, and secondary metabolites from beneficial microorganisms in the soil (Backer et al., 2018; Areche et al., 2022, 2023). This improves the plant's ability to take in water and thrive (Backer et al., 2018). To increase the nutritional value of staple crops including rice, millet, sorghum, wheat, maize, cassava, and sweet potato, agronomic biofortification is an efficient and quick way to repair soil (De Valença et al., 2017; Cotrina Cabello et al., 2023; Younas et al., 2023).

Among the many methods farmers employ to improve plant development, tillage is an intriguing one. Depending on the soil type, tillage should be performed once a year to restore soil health. If you want to combine organic matter and inorganic fertilisers into the soil as quickly as possible, mechanical tillage is the way to go. This method of soil preparation eliminates weeds and hard/compact soil while also smoothing the top layer of soil, promoting the release of nutrients via the decomposition of organic matter, and generating soil aeration. Combinatorial effects of tillage, organic fertilisers, and a little quantity of inorganic fertilisers assist fulfil the target crop nutritional value and soil fertility even under difficult circumstances (Patil et al., 2015). Human actions have led to a decrease in farmable land and the polluting of water sources, both of which inhibit plant development. In addition to improving agricultural yields, good fertiliser management in the field has significant ecological and economic effects. Only a small number of minerals, including iodine and zinc, are now amenable to this method. Due to its quick excitation and limited mobility in the phloem, it is unsuccessful with other nutrients such as iron. As a result, the success rate varies depending on location. Irrigation water can only provide a limited range of micronutrients, and the potential toxicity of some of these elements might have unintended consequences for ecosystem health. Conventional breeding or focused genetic engineering may add micronutrients directly to cereal seeds, which is an alternative to fortification via agricultural management and food processing (Zimmermann and Hurrell, 2002).

8. Metabolic engineering

Biofortification via metabolic engineering may provide a solution when the natural diversity in sexually compatible germplasm is inadequate to provide appropriate micronutrient levels in a given crop through traditional breeding. This is the true for a number of micronutrients present in rice, including iron, provitamin A, and folates. There is tremendous potential for reducing micronutrient shortages by increasing the Fe and Zn content of rice, which is eaten by almost 3.5 billion people. When considering bioavailability, it is estimated that an increase in zinc concentration from 16 ppm to 18 ppm will provide an additional 30% of the EAR in women and children, and an increase in iron concentration from 2 ppm to 13 ppm will provide an additional 30% of the EAR in children when assuming a bioavailability of 10%. 7. Polished grains are representative of the energy-dense white rice ingested by people with micronutrient shortages, making the micronutrient content of these grains particularly significant. Polished rice germplasm collections only include a small range of diversity for iron, limiting the use of traditional breeding for this characteristic. Zinc concentrations of 28 ppm are, nevertheless, possible due to the presence of enough natural variation. Conventionally bred high-zinc rice varieties have been introduced in Bangladesh, and similar varieties have been introduced or are in development for a number of other nations. Genetic engineering may be used to increase micronutrient content in agricultural plants in situations when traditional breeding is hampered by a lack of genetic diversity. The production of enriched Fe and Zn rice by transgenic methods31 has been made possible by the identification of the vast majority of the essential genes involved in Fe and Zn absorption, transport, and storage. At the same time, a high-yielding variety was able to significantly boost its Fe (to 15 ppm) and Zn (to 45 ppm) in polished grain without increasing its absorption of harmful heavy metals (cadmium, arsenic, and lead). This transgenic variety has a much greater concentration of Zn than the commercially available, normally developed Zn cultivars. It is advantageous to have numerous high-yielding cultivars that combine Fe and Zn features with other micronutrients and agronomic factors. It is important to note that the amount and bioavailability of the various minerals in the soil are crucial to the effectiveness of biofortification in terms of mineral micronutrient increase. Foliar or soil fertilization may be used to supplement the substrate's lack of the latter. When used in conjunction with metabolic engineering and breeding methods, these agronomic practices may help improve crop yields even under marginal growing conditions. Furthermore, recent technologies have significant role in crop growth improvement and development.

9. Future prospects

Because of rising demand for food and fuel, farmers are focusing on breeding higher-yielding strains of key crops. Enhancing the rate of photosynthesis by genetic modification has gained popularity in recent years as a method of increasing crop yields. Modeling methods and preliminary research into the over-expression of specific genes in a range of transgenic plants provide supportive evidence. The hypothesis that simultaneously influencing numerous targets in CBC, photorespiration, and electron transport would have a synergistic impact and lead to even bigger gains in yield was later substantiated by a multi-targeted strategy to genetic modification. With addition, boosting CO_2 absorption has the potential to improve nutritional content; growing carrots, strawberries, tomatoes, celery, and citrus in high CO_2 resulted in a rise in vitamin C content. These findings also imply that boosting plant vitamin content may be possible by manipulation of photosynthesis to promote CO_2 uptake without raising atmospheric [CO_2]. This issue, however, might be more nuanced and species-specific. Soybeans grown at high CO_2 increased in seed output.

The scientists also found an uptick in vitamin E levels in these plants. These findings indicate that climate change might drastically affect the nutritional content of our crops as a consequence of worldwide changes in atmospheric CO_2, temperature, and rainfall.

Implementing methods like genetic engineering and genome editing to manipulate endogenous genes are at the forefront of agricultural research thanks to advances in biotechnology. New tools, such as vectors for multiple gene insertion and tissue-specific promoters are needed to generate plants with sustainable increases in yields and nutritional quality and the ability to adapt successfully to changing environmental conditions. Changing how people think about genetic engineering and genome editing is essential for these biotech initiatives to deliver on their potential. For instance, a group of European scientists created 'Golden Rice,' biofortified with pro-vitamin A, to counteract vitamin A deficiency-related blindness and early mortality in people that feed on nutrient-poor white rice. Unfortunately, despite Golden rice's best efforts, millions of people throughout China, Bangladesh, and other parts of South and Southeast Asia have reportedly starved to death or gone blind in the intervening 20 years. While its opponents have called golden rice "fool's gold" and "propaganda for GM technology," its proponents have called the 20-year delay in its implementation "a crime against mankind. Finally, regulatory processes for the approval of GM crops are in existence in all countries. However, they vary widely and are sometimes confounded by non-science-based systems. Adoption of these technologies on a global scale may need a more streamlined long-term strategy.

10. Conclusion

Researchers have found that increasing the expression of genes involved in provitamin A, folate, and vitamin C metabolism increases the corresponding micronutrient levels in corn, and that increasing the expression of all three genes simultaneously increases the corresponding micronutrient levels, creating multivitamin corn. This study paves the way for engineering high-yielding multivitamin crops to combat "hunger" and "hidden hunger" in vulnerable communities by altering photosynthesis and vitamin metabolism. Evidently, biofortification has a lot of potential for enhancing the nutritional content of staple crops. Several necessary minerals and vitamins might have their bioavailability enhanced via the application of recombinant DNA technology. Generally present in fortified food components, external fortification of these nutrients has minimal usefulness. Most people in the developing world live in rural areas, and they lack the resources to buy and consume fortified foods. As the technique may be distributed with seeds of the main staple crops, biofortification can be of significant use in satisfying the nutrient needs of low-income communities at a reasonable cost.

One of the biggest issues, however, is that so few biofortified transgenic crops have been released for widespread commercial production. Even the well-recognized Golden Rice, which has been biofortified with Vitamin A, was only recently certified by the FDA after more than a decade of passing regulatory standards. After extensive biosafety evaluations by the Philippine Department of Agriculture's Bureau of Plant Industry, Golden Rice was given the green light for human consumption, animal feed, and industrial processing in the Philippines on December 18 of 2018. In order for society to reap the benefits of new technology, authorities must reevaluate existing procedures in order to eliminate any needless rules based on "precautionary" concepts. Such a strategy would have far-reaching positive effects for society and play a crucial role in ensuring the availability of safe and nutritious food for everybody.

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