Chapter III : Micronutrients and Biofortification

Nowadays, more than 100 chemical elements are known, but only 17 are considered essential for plant growth and development. These essential elements are classified into three categories: primary macronutrients (Nitrogen, Phosphorus, and Potassium), secondary macronutrients (Calcium, Magnesium, and Sulfur), and micronutrients (Iron, Zinc, Manganese, Copper, Boron, Molybdenum, Chlorine, and Nickel). Among these 17 essential elements, Carbon, Hydrogen, and Oxygen are obtained from air and water, while the other 14 elements are mainly absorbed by plant roots from the soil.

Micronutrients are essential mineral elements required by plants in very small amounts, generally less than 100 mg kg^{-1} of plant dry matter. Despite their low concentrations, they play vital roles in numerous physiological and biochemical processes, including enzyme activation, photosynthesis, respiration, hormone synthesis, and the maintenance of plant structural integrity. Even mild micronutrient deficiencies can negatively affect plant growth, productivity, and reproductive development.

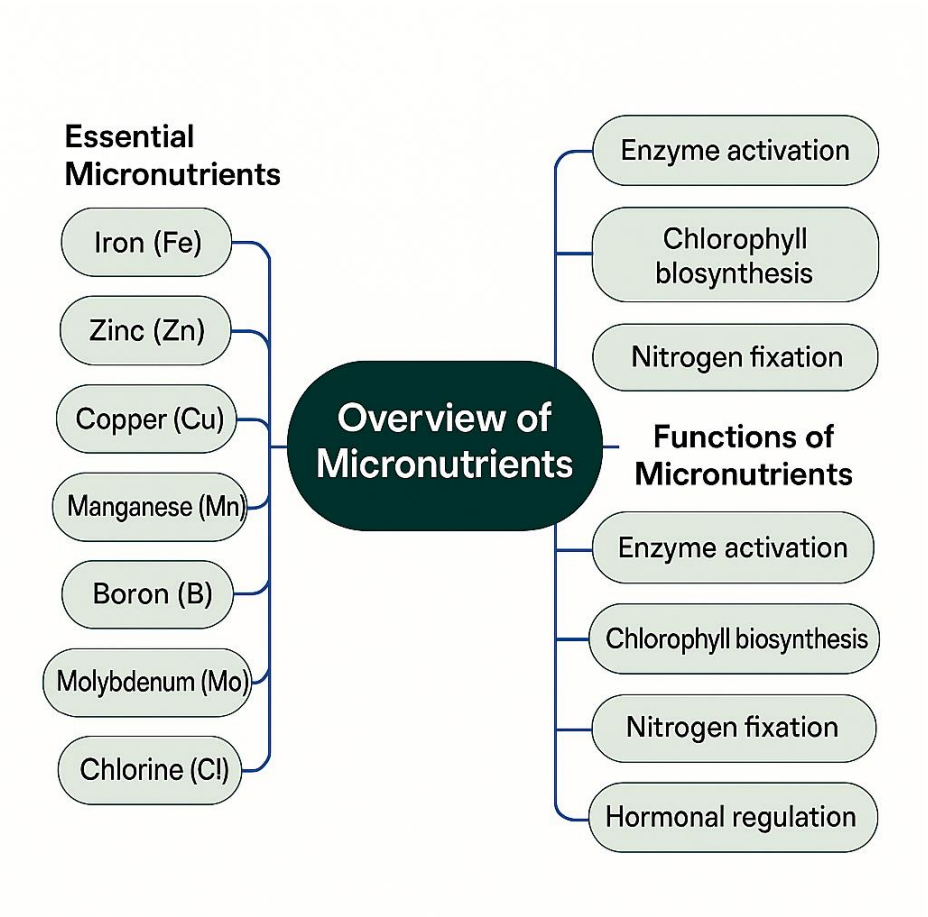


Figure 1 : Overview of Micronutrients.

There are two main types of micronutrient deficiencies:

-Absolute or true deficiency : This occurs when the soil contains little or no available reserves of the essential element. In this case, applying the missing element to the soil can generally correct the deficiency.

-Conditional, relative, or induced deficiency : In this case, the element is present in the soil but is unavailable for plant uptake. This type of deficiency is common under agricultural conditions and may result from factors such as high soil pH, ion antagonism, excessive organic matter, or nutrient losses through leaching. Correcting the soil conditions that limit nutrient availability is therefore necessary to restore proper plant uptake.

1. Specific Roles : Iron (Fe), Zinc (Zn), Boron (B), and Manganese (Mn)

1.1. Iron (Fe)

- **Physiological Roles**

Iron is an essential micronutrient required in relatively large amounts compared with other micronutrients.

-It is a component of numerous enzymes and proteins, both heme and non-heme.

-It is involved in chlorophyll biosynthesis, although iron is not a component of the chlorophyll molecule.

-It plays a key role in electron transport during photosynthesis and respiration through proteins such as cytochromes and ferredoxin.

-It is a component of heme-containing enzymes, including catalase, peroxidase, and cytochrome oxidase.

-It contributes to the activity of enzymes such as nitrate reductase.

-It plays an important role in redox reactions and helps protect plants against oxidative stress.

- **Deficiency**

-Iron deficiency is commonly associated with high soil pH, particularly in calcareous soils, poor soil aeration, and high levels of zinc (Zn) or manganese (Mn), which can interfere with iron availability.

-Since iron is relatively immobile within the plant, deficiency symptoms appear first in young leaves.

-The main symptom is interveinal chlorosis: young leaves become pale green or yellow while the veins remain green.

-As the deficiency becomes more severe, plant growth is reduced, which may lead to lower crop yield.

-Sensitive crops include bean, tomato, cauliflower, soybean, citrus, and grapevine. Cereals are generally less sensitive to iron deficiency.

-Lupin is particularly sensitive to iron deficiency and iron chlorosis in calcareous soils.

-In grapevine, iron chlorosis is particularly common in young plantations, especially during the first two to three years.



Figure 2 : Iron Deficiency Symptoms in Tomato.

- **Correction of Deficiency**

Several approaches can be used to correct iron deficiency, including soil application, foliar spraying, and fertigation. Iron can be supplied in different forms, including iron salts and iron chelates. Foliar application of liquid iron nitrate can be effective when combined with an appropriate agent that facilitates its penetration into plant tissues.

Iron chelates have also become an important method for correcting iron chlorosis. They can be applied to the soil or directly to the foliage. Their effectiveness depends strongly on soil pH. In alkaline soils with high Ca^{2+} concentrations, some chelates may become less effective because calcium can form complexes with the chelating agent, while iron may precipitate as iron oxides. Therefore, Fe-EDDHA is generally more suitable for high-pH and calcareous soils, whereas Fe-DTPA can be effective under acidic to moderately acidic conditions.

Because iron chelates are relatively expensive, their use may be less economically suitable for large-scale crops with low or moderate returns. Preventive soil management can also help reduce iron chlorosis. Incorporating organic matter and appropriate acidifying materials can improve iron availability, while reducing soil compaction and improving drainage can help maintain favorable conditions for iron uptake.

1.2. Zinc (Zn)

- **Physiological Roles**

Zinc (Zn) is an essential micronutrient involved in numerous metabolic and enzymatic processes in plants.

-It acts as an activator or structural component of several metalloenzymes, including carbonic anhydrase, which is important for CO_2 utilization and photosynthesis.

-It activates various dehydrogenases, including glutamate dehydrogenase, lactate dehydrogenase, and alcohol dehydrogenase, thereby contributing to carbohydrate and protein metabolism.

-Zinc is involved in the activity of several proteases and peptidases, which participate in protein metabolism.

-It contributes to nucleic acid metabolism and is required for the activity of enzymes involved in DNA and RNA synthesis, including DNA and RNA polymerases.

-Zinc plays an important role in the synthesis of indole-3-acetic acid (IAA), a major plant growth hormone (auxin), and therefore contributes to normal plant growth and development.

-It contributes to carbohydrate and protein metabolism and supports overall plant metabolic activity.

-Adequate zinc nutrition can contribute to plant resistance against certain fungal diseases.

- **Deficiency**

-Zinc (Zn) is strongly adsorbed by soil particles and is mainly retained in the soil complex in ionic forms such as Zn^{2+} and hydrolyzed species. As a result, its concentration and mobility in the soil solution are generally low.

-Soil pH is one of the most important factors affecting zinc availability. As soil pH increases, zinc becomes less mobile and less available for plant uptake. In contrast, acidification can increase zinc availability.

-Zinc deficiency can negatively affect fruit formation and reproductive development, leading to reduced seed production and smaller fruits.

-In monocotyledonous plants, particularly maize, zinc deficiency is characterized by pale green to yellow or whitish chlorotic bands on both sides of the leaf midrib. Under severe deficiency, these areas may become necrotic, and young leaves can turn almost white or pale yellow, a condition known as “white bud.”

-In fruit trees, a typical symptom is rosetting, in which small, narrow, closely spaced leaves develop at the ends of new shoots. This condition is commonly referred to as “little leaf.”

-Zinc deficiency can also cause leaf deformation and premature leaf drop, as well as fruit deformation, partly due to reduced auxin synthesis.

-In citrus plants, zinc deficiency may appear as leaf deformation and interveinal chlorosis, producing a yellowish or cream-colored mottled pattern against a dark green background. This condition is known as “mottle leaf” or “bottle leaf.”



Figure 3 : Zinc Deficiency Symptoms in Citrus Plants.

- **Correction of Deficiency**

-Zinc deficiency can be corrected through either soil application or foliar spraying. Soil application is generally more effective, particularly in severe cases, and cannot always be replaced by foliar application.

-Zinc sulfate ($ZnSO_4$) is widely used because of its high solubility. A typical application rate is about 25–50 kg/ha of $ZnSO_4 \cdot 7H_2O$ during soil preparation.

-Zinc oxide (ZnO) can also be used effectively, especially when applied in a finely ground form.

-Zinc-fortified fertilizers or Zn-coated urea can provide a sustained supply of zinc to plants.

-In acidic soils, foliar application of zinc may be useful because soluble zinc sources such as $ZnSO_4$ can be readily leached from the soil.

-Excessive phosphorus fertilization should be avoided because high phosphorus availability can interfere with zinc uptake.

-Good soil management and appropriate zinc fertilization help maintain adequate Zn availability and prevent deficiency.

1.3. Boron (B)

- **Physiological Roles**

Boron (B) is an essential micronutrient absorbed by plants mainly in the form of boric acid (H_3BO_3), particularly in soils with a pH below 9.

-It plays an important role in cell wall development by promoting the cross-linking of pectic polysaccharides, thereby contributing to cell wall structure and stability.

-Boron is involved in the transport and utilization of sugars and other assimilates, particularly through the phloem.

-It contributes to hormone transport and regulation, supporting normal plant growth and development.

-Boron is involved in meristematic activity and is essential for the normal growth of actively dividing tissues.

-It contributes to ribosome formation and protein synthesis.

-It influences the uptake and utilization of potassium, phosphorus, magnesium, and other mineral cations.

-Boron is particularly important for reproductive development, including pollen viability, pollen germination, fertilization, and seed set.

-Boron deficiency can lead to reproductive tissue sterility or malformation, as well as impaired growth of young and meristematic tissues.

- **Deficiency**

-The average boron content of soils generally ranges from 1 to 2 ppm. Boron deficiency may occur when soil boron levels fall below approximately 0.6 ppm.

-Boron availability generally decreases as soil pH increases. A negative relationship exists between soil pH and boron availability, particularly at pH values above 6.5.

-Severe boron deficiency affects actively growing tissues, especially the shoot and root meristems, because boron is relatively immobile within the plant.

-Young leaves may become deformed, wrinkled, thick, and brittle, often with a bluish-green color. Irregular interveinal chlorosis may also develop.

-As the deficiency progresses, the terminal buds and growing points may become brown or black, dry out, and eventually die. Stems and leaves may become rigid, brittle, and fragile.

-The root system may develop thick, short, brittle, or necrotic roots. Root growth is often severely restricted under prolonged boron deficiency.

-In sugar beet, severe boron deficiency can cause heart rot. Young leaves become curled, stunted, dry, and darken. Brown lesions and transverse cracks may appear on the upper part of the petiole. As the disorder progresses, the growing points die, the crown becomes necrotic and begins to rot, and the center of the beet may become hollow and black.

-Internal and external corky tissues are characteristic symptoms of boron deficiency in several crops, including tomato, cauliflower, citrus, and apple.

-Reproductive development can also be affected, resulting in poor flowering, reduced pollen viability, poor fruit set, and fruit abnormalities.

-Dicots are generally more sensitive to boron deficiency than monocots, although sensitivity varies considerably among plant species and, in fruit trees, among cultivars.

-In apple and pear, one of the most characteristic symptoms is the development of corky brown lesions both inside the fruit and on the fruit surface.



Figure 4 : Boron Deficiency Symptoms in Citrus Plants.

Correction of Deficiency

-Boron deficiency can be corrected through soil application or foliar spraying.

-For annual crops, boron-containing fertilizers are commonly applied to the soil, often mixed with other fertilizers, to provide a consistent supply of boron throughout the growing season.

-Foliar application is particularly useful for actively growing crops and perennial crops, allowing boron to be supplied directly to the leaves and rapidly correcting deficiency symptoms.

-Legumes and certain root crops generally require approximately 2–4 kg of boron per hectare, depending on the crop and soil conditions.

-For sugar beet, a recommended application rate is approximately 2–3 kg B/ha, which can improve both root yield and technological quality.

-Because the optimal boron rate is relatively narrow and excessive boron can cause toxicity, application rates should be adjusted according to crop requirements and soil boron status.

1.4. Mananese (Mn)

- **Physiological Roles**

Manganese (Mn) is an essential micronutrient that acts primarily as an activator of numerous enzymes involved in oxidation–reduction reactions, decarboxylation, and the transfer of chemical groups.

-It plays a key role in photosynthesis, particularly in the water-splitting reaction of Photosystem II, which is essential for the release of oxygen.

-Manganese contributes to chloroplast development and helps maintain normal photosynthetic activity.

-It is involved in nitrogen metabolism, particularly through its role in the activity of nitrate reductase. Manganese deficiency can reduce nitrate reductase activity, resulting in nitrate accumulation in plant tissues.

-It contributes to carbohydrate metabolism and the translocation of carbohydrates within the plant.

-Manganese is involved in the synthesis of aromatic amino acids and various secondary metabolites.

-It contributes to water regulation in plants and may influence water uptake and transport.

-Manganese plays an important role in plant defense and can increase resistance to certain diseases, including some viral diseases such as beet mild yellowing virus (BMYV).

- **Deficiency**

-Manganese deficiency is more likely to occur in soils rich in organic matter, particularly under neutral to alkaline pH conditions.

-Increasing soil pH reduces manganese availability by promoting the oxidation of soluble Mn^{2+} and its complexation with organic matter. A one-unit increase in pH can reduce the solubility of Mn^{2+} by approximately 100-fold.

-Some forms of organic matter, particularly humic acids, can bind manganese in forms that are less available for plant uptake.

-In monocotyledonous plants, deficiency symptoms often appear as grayish-green spots on the leaves, while the main veins remain green. The leaves may also become folded near the base. Under severe deficiency, chlorosis can spread over the entire leaf.

-In dicotyledonous plants, manganese deficiency is characterized by small yellow spots or speckles on the leaves, while the veins generally remain green. As the deficiency progresses, necrotic areas may develop and can sometimes lead to perforation of the leaves.

-In fruit trees, particularly grapevine, symptoms typically begin on older leaves as diffuse interveinal chlorosis, often extending toward the leaf margins. Peach and cherry trees are among the most sensitive fruit species.

-In citrus plants, symptoms usually appear first on young leaves and may later affect older leaves if the deficiency persists. A characteristic symptom is the development of light-green mottling along the leaf margins.



Figure 5 : Manganese Deficiency Symptoms in Citrus Plants".

- **Correction Deficiency**

-Foliar application is generally the most effective and economical method for rapidly correcting manganese deficiency, particularly as a curative treatment.

-Manganese sulfate ($MnSO_4$) is one of the most effective sources for foliar application. For manganese-deficient cereal crops, approximately 3–5 kg $MnSO_4 \cdot H_2O$ per hectare can be applied as a foliar treatment, according to the product formulation and recommended application rate.

-Soil application can be less effective in alkaline or well-aerated soils because Mn^{2+} can be rapidly oxidized into less soluble forms.

-Manganese fertilizers include manganese sulfate ($MnSO_4$), manganese oxide (MnO), manganese carbonate ($MnCO_3$), manganese dioxide (MnO_2), and manganese chelates such as Mn-EDTA.

-Maintaining soil pH below approximately 6.5 can improve manganese solubility and availability.

-For soil application, manganese can be incorporated with an acidifying fertilizer to help maintain manganese in a more soluble form and reduce its oxidation.

-Adequate soil drainage should be maintained to avoid excessive manganese accumulation under waterlogged conditions, which may lead to manganese toxicity.
-Mn-EDTA can also be used as a source of manganese, particularly for foliar application or where a chelated form is preferred.

2. Iron Acquisition Strategies : Strategy I (acidification/reduction) and Strategy II (siderophores/phytosiderophores).

2.1. Strategy I (acidification/reduction)

Strategy I is mainly used by dicotyledonous plants and non-grass monocotyledonous plants. It involves three main steps :
-Proton secretion and rhizosphere acidification : Plant roots release protons (H^+) into the rhizosphere through the activity of H^+-ATPase. This lowers the pH around the roots and increases the solubility of iron, particularly Fe(III) present in iron oxides. As a result, more iron becomes available for uptake by the plant.
-Reduction of Fe(III) to Fe(II) : At the root surface, ferric reductase oxidoreductase (FRO) reduces Fe(III) to Fe(II). Fe(II) is more readily absorbed by plant roots. This reduction process is less efficient under alkaline conditions and in soils with high bicarbonate concentrations, which can lead to iron deficiency.
-Uptake of Fe(II) : The resulting Fe(II) is transported into root cells through divalent metal transporters, particularly iron-regulated transporter (IRT) proteins.
Plants can also release specific compounds into the rhizosphere that enhance iron acquisition. For example, under iron deficiency, Arabidopsis thaliana produces coumarin compounds such as scopoletin, scopolin, and fraxetin. These compounds can form soluble complexes with Fe(II) and Fe(III), helping maintain iron in a soluble form and reducing its precipitation as iron hydroxides. Some plants can also directly absorb Fe(III)–coumarin complexes. In addition, flavins may contribute to iron acquisition by facilitating the reduction and uptake of iron.

2.2. Strategy II (siderophores/phytosiderophores).

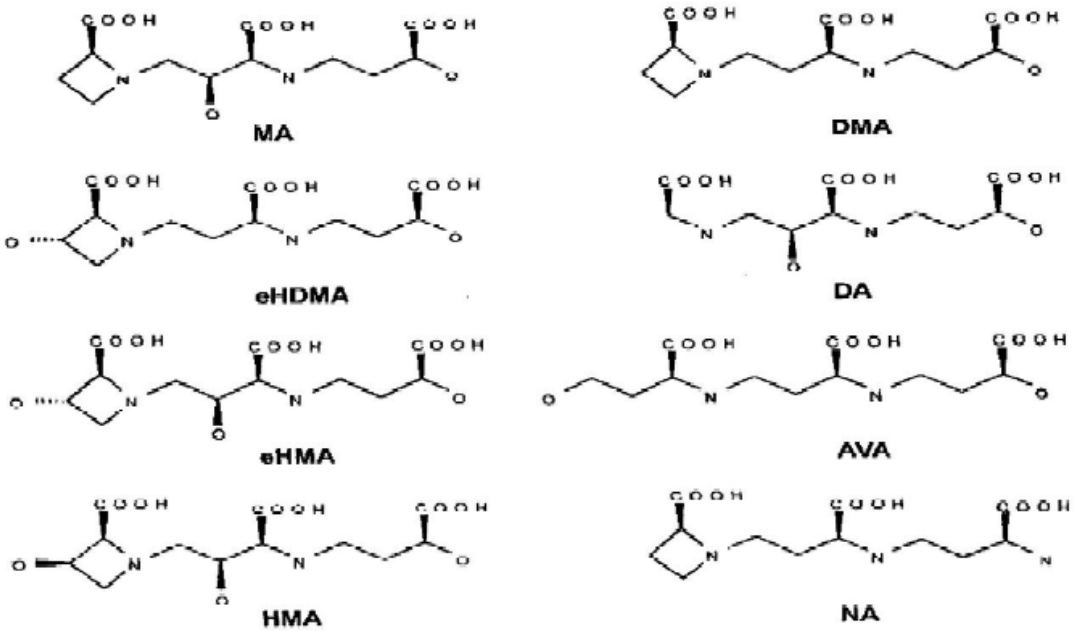
Phytosiderophores are organic chelating compounds secreted by the roots of various grass species, including oat, barley, wheat, and rice. They bind iron (Fe) in the soil, forming Fe–phytosiderophore complexes. These complexes are then taken up by the roots through specific transporters located in the plasma membrane.
Strategy II is mainly found in monocotyledonous plants belonging to the grass family (Gramineae). When iron is deficient, these plants synthesize phytosiderophores belonging to

the mugineic acid family. These compounds are released into the rhizosphere through specific transporter proteins, particularly TOM1.

Once released, phytosiderophores bind Fe(III) and form soluble Fe(III)–phytosiderophore complexes. These complexes are then taken up by the roots through YS1/YSL transporters located in the root plasma membrane.

Unlike Strategy I, Strategy II is less affected by high soil pH and high bicarbonate concentrations. Therefore, plants using Strategy II are generally more efficient at acquiring iron from calcareous soils, where iron is poorly soluble.

Nine different structures of mugineic acid family phytosiderophores have been identified so far. Their synthesis begins with S-adenosyl-L-methionine and involves three successive enzymatic reactions. These reactions are catalyzed by nicotianamine synthase (NAS), nicotianamine aminotransferase (NAAT), and deoxymugineic acid synthase (DMAS), leading to the production of deoxymugineic acid (DMA). DMA then serves as a precursor for the synthesis of other phytosiderophores belonging to the mugineic acid family.



Figue 6 : Structure of mugineic acid derivatives and nicotianamine.

The two strategies of iron acquisition involve different transport systems for taking up iron from the soil.

In Strategy II plants, the YS1 (Yellow Stripe 1) transporter is responsible for the uptake of Fe(III)–phytosiderophore complexes. YS1 was first identified in maize and belongs to the

oligopeptide transporter (OPT) family. It was named after the yellow-stripe phenotype observed in maize mutants unable to efficiently take up phytosiderophores. Under iron deficiency, grasses increase both the release of phytosiderophores and the abundance of YS1 transporters, thereby enhancing iron uptake.

In Strategy I plants, IRT1 (Iron-Regulated Transporter 1), which belongs to the ZIP (ZRT/IRT-related protein) family, is considered one of the main transporters responsible for Fe^{2+} uptake into root cells. Its importance is demonstrated by the severe iron-deficiency symptoms observed in plants lacking functional IRT1. The IRT1 gene was first identified in Arabidopsis thaliana and related genes have subsequently been found in other Strategy I plants, such as tomato and pea.

Interestingly, IRT1-related proteins are also present in some Strategy II plants. For example, a rice iron transporter called OsIRT shows high similarity to IRT1, indicating that some components of iron uptake systems may be shared between Strategy I and Strategy II plants.

In addition to IRT1 and YS1, other iron-regulated transporters have been identified. IRT2 is closely related to IRT1 and has a similar expression pattern, but it appears to have a smaller role in iron uptake. Although both IRT1 and IRT2 can restore iron uptake in iron-deficient yeast mutants, they do not appear to perform completely redundant functions in plants.

Once iron enters plant cells, it must be chelated because free iron is highly reactive and poorly soluble. In higher plants, the main chelating molecule is nicotianamine (NA), a non-proteinogenic amino acid that binds iron and other metal ions. NA is synthesized from L-methionine through the action of nicotianamine synthase.

In grasses, NA also serves as a precursor for the synthesis of mugineic acid family phytosiderophores. Although both Strategy I and Strategy II plants produce nicotianamine, only grasses synthesize and secrete phytosiderophores into the rhizosphere.

YSL (Yellow Stripe-Like) transporters are also found in Strategy I plants. For example, several YSL genes have been identified in Arabidopsis, suggesting that these proteins may have roles in the internal transport and homeostasis of metals rather than directly in iron uptake from the soil.

NRAMP proteins form another family of metal transporters that may contribute to iron homeostasis in plants. In Arabidopsis, AtNRAMP1, AtNRAMP2, and AtNRAMP4 are upregulated under iron deficiency, suggesting a role in the transport of iron and other metals.

Iron export from cells may involve ferroportin proteins, particularly FPT1 (also called IREG1 or MTP1). In Arabidopsis, FPT1 is expressed in vascular tissues, suggesting that it may contribute to iron transport and loading into the xylem.

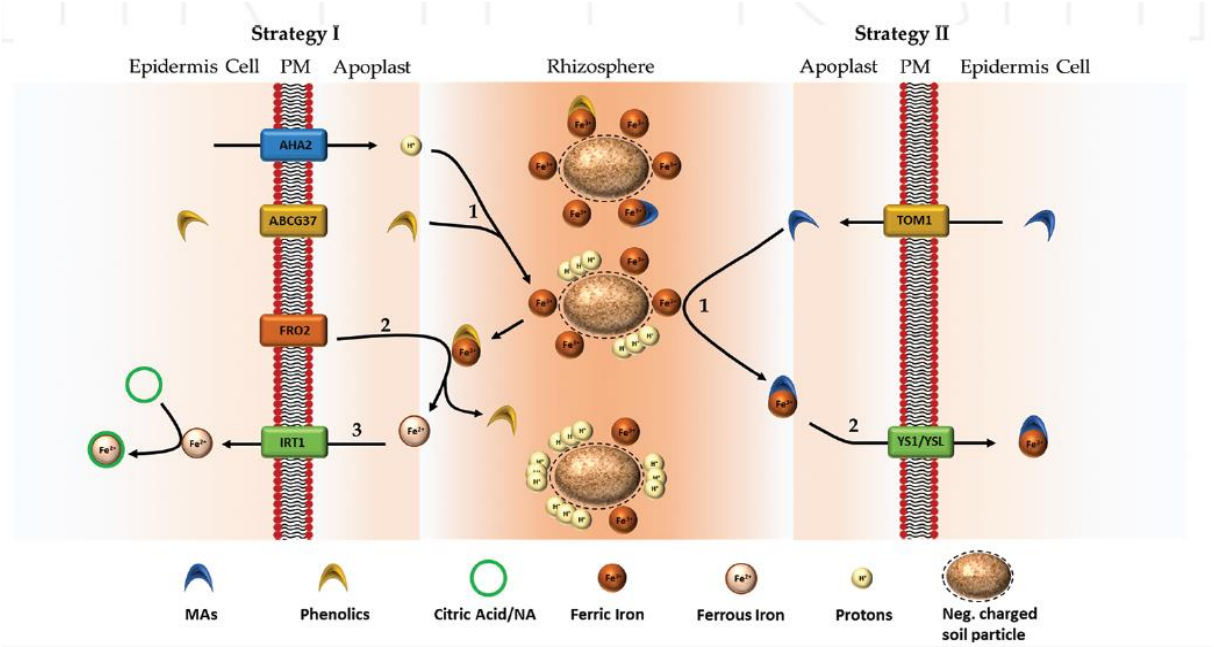


Figure 7 : Strategy I and Strategy II for Iron Acquisition in Plants. Strategy I, found mainly in dicotyledonous and non-grass monocotyledonous plants such as *Arabidopsis thaliana*, involves three main steps. First, root proton pumps acidify the rhizosphere, increasing Fe^{3+} solubility. Phenolic compounds released by the roots can further enhance iron mobilization. Second, the enzyme FRO2 reduces Fe^{3+} to Fe^{2+}. Finally, Fe^{2+} is taken up by root cells through the IRT1 transporter. Once inside the plant, iron can be chelated by compounds such as citrate and nicotianamine and transported to other tissues. Strategy II, characteristic of grasses such as maize and rice, involves the release of phytosiderophores into the rhizosphere by the TOM1 transporter. Phytosiderophores chelate Fe^{3+} and form soluble Fe^{3+}–phytosiderophore complexes. These complexes are then taken up by the roots through YS1 in maize and YSL transporters in other grasses.

3. Biofortification : Improving the micronutrient content of crops to enhance human health.

3.1. Definition

Biofortification is the process of increasing the concentration and bioavailability of essential nutrients in the edible parts of crops through agronomic practices or genetic approaches. It is considered a promising strategy for addressing malnutrition and hidden hunger, particularly

among populations with limited access to a diverse and nutritious diet. By improving the nutritional value of staple crops, biofortification can help increase the intake of essential vitamins and minerals.

3.2. Types of Biofortification

3.2.1. Agronomic Biofortification

Agronomic biofortification involves increasing the concentration of essential micronutrients in edible plant tissues through agricultural practices, mainly the application of micronutrient fertilizers. It is a relatively rapid and practical approach that can improve both the nutritional quality and, in some cases, the yield of crops.

Micronutrients such as iron (Fe), zinc (Zn), selenium (Se), iodine (I), manganese (Mn), and copper (Cu) can be supplied to crops through different methods.

- **Soil Application**

Micronutrient fertilizers are applied directly to the soil, where nutrients become available for uptake by plant roots. The absorbed nutrients are subsequently transported to different plant organs, including the edible parts.

- **Foliar Application**

Foliar fertilization involves spraying micronutrient solutions directly onto the leaves. It is a rapid and effective method for increasing the concentration of nutrients in plant tissues, particularly in the edible parts of crops. It can also help correct nutrient deficiencies during plant growth.

- **Seed Priming**

Seed priming involves soaking seeds in solutions containing essential nutrients before sowing. This treatment can stimulate seed metabolism, improve germination and seedling vigor, and increase the micronutrient content of harvested crops. Nutrients such as zinc can be used for seed priming.

Agronomic biofortification is relatively simple and rapid, but it may require repeated fertilizer applications and, if poorly managed, can have environmental impacts.

3.2.2. Conventional Plant Breeding

Conventional breeding uses the natural genetic variation present within crop species to develop varieties with higher nutritional value. Plant breeders identify varieties naturally rich in essential micronutrients and cross them with high-yielding varieties. The resulting offspring are then selected over successive generations for desirable nutritional and agronomic traits.

This approach can produce biofortified crops adapted to specific regions and nutritional needs. However, it is generally time-consuming and may require several generations to develop a new variety.

3.2.3. Genetic Engineering

Genetic engineering involves modifying the genetic material of a plant to increase the concentration or bioavailability of essential nutrients. Specific genes can be introduced, modified, or regulated to enhance nutritional traits that may be difficult to obtain through conventional breeding.

This approach can provide substantial increases in nutrient levels and allows the introduction of traits that are absent or poorly expressed in the original crop. A well-known example is Golden Rice, which was genetically modified to produce β-carotene, a precursor of vitamin A, in the rice grain.

3.3. Targeted Nutrients For Biofortification

- **Iron (Fe)**

Iron is an essential micronutrient that plays a key role in hemoglobin formation and oxygen transport. It is also involved in energy production, DNA synthesis, and several metabolic processes. Iron deficiency is a major global nutritional problem and can lead to microcytic anemia, reduced work capacity, impaired immune function, and adverse pregnancy outcomes. Iron biofortification aims to increase the iron concentration and bioavailability of edible crops such as rice, wheat, and beans, thereby improving dietary iron intake.

- **Zinc (Zn)**

Zinc is an essential micronutrient for both plants and humans. In humans, it plays important roles in immune function, DNA and protein synthesis, wound healing, and the metabolism of carbohydrates, proteins, and lipids. Zinc deficiency is a major public health concern and can increase susceptibility to infections, impair growth and development, and affect immune function.

Zinc deficiency in humans is often associated with zinc-deficient soils, particularly in regions where diets rely heavily on plant-based foods. Zinc biofortification can help address this problem by increasing the zinc concentration and nutritional value of edible crops. Agronomic zinc biofortification has been successfully applied to a wide range of crops.

- **Iodine (I)**

Iodine is an essential micronutrient for humans and is required for the normal functioning of the thyroid gland, energy metabolism, and regulation of body temperature. Although iodine is

not considered essential for plants, its application can increase iodine accumulation in plant tissues and may improve crop yield in some cases.

Iodine deficiency affects a significant proportion of the global population and can lead to health problems such as goiter, hypothyroidism, impaired growth, infertility, and intellectual disabilities. Iodine biofortification of crops is therefore a promising strategy, particularly in regions where iodine deficiency is common and diets rely heavily on plant-based foods.

Agronomic biofortification, through the application of iodine to crops, can increase the iodine content of edible plant parts and contribute to improving dietary iodine intake.

- **Selenium (Se)**

Selenium is an essential trace element for human health. It is incorporated into selenoproteins, such as glutathione peroxidase, which contribute to antioxidant defense and support normal immune function. Selenium deficiency affects a large number of people worldwide.

Although selenium is not considered an essential element for plants, low concentrations can have beneficial effects in some crops by enhancing antioxidant activity and improving plant growth and quality. For example, selenium application can delay tomato fruit ripening by reducing ethylene production and strengthening the antioxidant defense system.

Plants can absorb selenium from the soil, but its availability varies depending on soil properties and the chemical form of selenium. In selenium-deficient soils, selenium biofortification can increase its concentration in edible plant tissues. This can be achieved through selenium fertilizers, selenium-enriched organic amendments, irrigation water, or seed treatments.

3.3. Target Crops for Biofortification

- **Cereals**

Cereals such as rice, wheat, and maize are major staple foods and important sources of calories for large populations. However, they are often poor sources of essential micronutrients and some nutrients, contributing to hidden hunger. Biofortification can improve their nutritional value by increasing levels of iron (Fe), zinc (Zn), protein, and provitamin A.

-Rice : Polishing removes a significant proportion of iron and zinc from rice grains, making polished rice a poor source of micronutrients. Biofortified rice varieties can help improve zinc and protein intake. For example, some improved rice varieties have higher zinc concentrations, while protein-rich varieties contain substantially more protein than conventional varieties.

-Wheat : Wheat is another major staple crop. Breeding programs aim to develop varieties with higher concentrations of iron and zinc. Although these minerals are concentrated in the aleurone layer, their bioavailability can be reduced by phytate. Therefore, increasing both mineral concentration and bioavailability is important for wheat biofortification.

-Maize : Maize is particularly suitable for provitamin A biofortification because it naturally contains carotenoids such as β-carotene, α-carotene, β-cryptoxanthin, lutein, and zeaxanthin. Provitamin A-rich maize can help address vitamin A deficiency, especially where supplementation is difficult or expensive. Traditional maize is also relatively low in protein and essential amino acids such as lysine and tryptophan. Quality Protein Maize (QPM) varieties have been developed with higher levels of these amino acids, improving the nutritional quality of the crop.

- **Pulses**

Pulses are important sources of protein, minerals, and other essential nutrients, particularly in developing countries. Their biofortification can help reduce malnutrition by increasing the nutritional value of commonly consumed foods.

Pulses also contribute to environmental sustainability because they fix atmospheric nitrogen, improving soil fertility.

Lentils and beans are promising crops for iron and zinc biofortification because they naturally have genetic variation in mineral accumulation. Conventional breeding can be used to select parent plants with high iron and zinc concentrations and develop improved varieties while maintaining desirable agronomic characteristics.

- **Vegetables and Fruits**

Vegetables and fruits are essential components of a healthy diet because they provide vitamins, minerals, dietary fiber, and other beneficial compounds. Regular consumption of a variety of fruits and vegetables is associated with better overall health and a lower risk of several chronic diseases.

Biofortification can further improve their nutritional value by increasing the concentration and bioavailability of essential nutrients. It may contribute to reducing micronutrient deficiencies, lowering the risk of chronic diseases, and improving overall health and well-being.

3.5. Scopes of Biofortification

- **Improving the Nutrition of Rural Populations**

Biofortification can help improve the nutritional status of rural populations, particularly those with limited access to diverse diets and formal nutrition programs. Biofortified crops can be developed to provide higher levels of essential micronutrients and address specific nutritional needs, especially among vulnerable groups such as women and children.

- **Economic Sustainability**

Biofortification can be economically sustainable because most of the major investment is made during the development of nutrient-rich crop varieties. Once biofortified varieties are available, their seeds can be distributed and cultivated repeatedly by farmers, reducing the need for continuous external investment. This makes biofortification a potentially sustainable approach to improving nutrition over the long term.

- **Cost-Effectiveness**

Biofortification is considered a cost-effective public health strategy because it can improve nutrient intake through commonly consumed staple crops without requiring major changes in dietary habits. Its relatively low implementation costs make it particularly suitable for populations affected by micronutrient deficiencies.