4. Mineral Nutrition

The absorption of water necessarily leads to the absorption of mineral elements, since the water in the soil contains dissolved nutrients (minerals). The mineral nutrition of the plant includes the mechanisms that ensure, after absorption, the transport, storage, and utilization of mineral ions necessary for the plant's metabolism and growth. These mechanisms take place in various organs of the vegetative system (roots, stems, and leaves).

The plant feeds on mineral salts found in the soil in the form of ions, which enter through the roots. Large root surfaces and active absorption systems explain why, despite the low concentration of ions in the soil solution, the acquisition of mineral nutrients by plants is a highly efficient process. Green plants draw essential mineral substances for their proper functioning from their surrounding environment (soil, water, and air). The absence or deficiency of these substances disrupts their development.

Essential elements (macro- and micro-elements):

An element is considered *essential* if, in its absence, the plant cannot complete its full life cycle from seed to seed. Its function cannot be replaced by another element, and it directly contributes to the plant's metabolic reactions.

Macroelements (in addition to **C**, **H**, and **O**) are **N**, **K**, **Ca**, **Mg**, **P**, **S**. Each of these represents at least 0.1% (from 0.1% to 4%) of the plant's dry matter. Nitrogen (N) is absorbed from the soil by the roots in the form of nitrate (NO_3^-) or ammonium (NH_4^+), or in some species, it comes from atmospheric nitrogen fixation by symbiotic bacteria. K, Ca, Mg, P, and S are absorbed from the soil in the form of ions: K^+, Ca^{2+}, Mg^{2+}, phosphate ($H_2PO_4^-$), and sulfate (SO_4^{2-}).

Microelements or **trace elements** play an important role in plant health and growth. They include Boron (B), Manganese (Mn), Zinc (Zn), Chlorine (Cl), Molybdenum (Mo), Cobalt (Co), and Copper (Cu). They are absorbed in the forms: Cl^-, Fe^{2+} or Fe^{3+} (depending on the species), Mn^{2+}, Zn^{2+}, borate ($H_2BO_3^-$), Cu^{2+}, Ni^{2+}, and MoO_4^{2-}.

The amounts of trace elements absorbed by plants are very small, but their role in overall plant nutrition is crucial. They are present in very low concentrations, not exceeding 0.01% of the plant's dry matter.

Non-essential elements

Non-essential (or facultative) elements are divided into two categories:

- **Useful elements:** These are beneficial or essential only for certain plants (e.g., Na, Si, Co, Al, Se, Ti).
- **Toxic elements:** These are elements that inhibit plant growth and development. Their effect may be linked to the blockage of an enzymatic system. It should be noted that when a mineral element is present at a high concentration, it can inhibit growth and development, thus becoming toxic**.**

Table: Mineral content of plant tissues (Gaudy, 2012)

Elements	Symbol	Concentration in Dry Matter (%)	Source
Carbon	C	44	CO_2 & HCO_3^-
Oxygen	O	43	H_2O
Hydrogen	H	6	H_2O
Macro-elements			**From the soil**
Nitrogen	N	1.5	NO_3^-, NH_4^+
Potassium	K	1	K^+
Calcium	Ca	0.5	Ca^{2+}
Magnesium	Mg	0.2	Mg^{2+}
Phosphorus	P	0.2	HPO_4^{2-} / $H_2PO_4^-$
Sulfur	S	0.1	SO_4^{2-}
Silica	Si	0.1	SiO_3^{2-}
Micro-elements			**From the soil**
Chlorine	Cl	0.01	Cl^-
Iron	Fe	0.01	Fe^{3+}
Manganese	Mn	0.005	Mn^{2+}
Zinc	Zn	0.002	Zn^{2+}
Boron	B	0.002	H_3BO_3
Copper	Cu	0.0006	Cu^{2+}
Nickel	Ni	0.0001	Ni^{2+}
Molybdenum	Mo	0.00001	MoO_4^{2-}

Macroelements

Nitrogen (N)

Nitrogen is an essential nutrient for plant growth and development. It is a constituent of amino acids, proteins, and several vitamins. Its deficiency causes a marked decrease in chlorophyll (chlorosis), resulting in yellowing of the leaves, followed by a slowdown and eventual halt of photosynthesis. This explains the importance of nitrogen nutrition in plant nutrition.

Phosphorus (P)

Phosphorus plays a role in energy transfer processes; the storage and transport of energy within cells (ATP), the transmission of hereditary traits (nucleic acids), photosynthesis, and carbohydrate degradation. Phosphorus is an important component of phosphorylated proteins (nucleoproteins, phosphoproteins, etc.). Moreover, many metabolic reactions require prior phosphorylation to occur. It is essential for flowering, earliness, fruit enlargement, and seed maturation.

Phosphorus deficiency:

- Slower growth;
- Reduced root development and plant density;
- Delayed flowering and maturation;
- Decrease in protein and vitamin production;
- Lower resistance to frost.

Potassium (K)

Potassium acts as an activator of various enzymes. It increases cell turgor pressure, regulates water balance in the plant, and reduces evaporation ; thereby increasing drought resistance. Potassium is the main ion in cytoplasmic solutions and plays a key role in both passive and active transmembrane exchanges within cells.

It improves chlorophyll assimilation efficiency and frost resistance. Legumes, potatoes, beets, maize, and oats have high potassium requirements.

Potassium deficiency:

- Less pleasant taste in fruits and vegetables;
- Reduced resistance to frost and drought;
- Increased transpiration and respiration;
- Poor storage quality of fruits and vegetables.

Magnesium (Mg)

Magnesium is a constituent of chlorophyll. It is also found in essential organic compounds such as pectin, and serves as an enzyme activator.

- It promotes the absorption and transport of phosphorus to the seeds, where it helps in lipid synthesis.
- Magnesium also prevents excessive potassium uptake by plants.

Calcium (Ca)

Calcium levels can be similar to those of potassium, but its mobility and distribution in plant tissues are quite different. It binds strongly to the carboxyl groups (–COOH) of hemicelluloses and pectic compounds (carbohydrate components of the plant cell wall that provide structure, stability, and flexibility).

Inside the vacuole, it participates in the electrical neutralization of anions (such as sulfates and phosphates). It also plays an essential role as a secondary biochemical messenger in the functioning of the plant's cellular machinery.

Microelements (Trace Elements)

Microelements, which are part of the structure of certain proteins, are particularly involved in oxidation-reduction reactions that ensure electron transfer in cellular metabolism.

- **Iron (Fe^{2+} or Fe^{3+}):** Part of protein complexes such as cytochromes and ferredoxins, responsible for electron transfer in the photosynthetic machinery of leaves. Iron is also part of certain respiratory enzymes, such as cytochrome oxidase.
- **Copper (Cu^{2+}):** Acts in similar mechanisms as iron.
- **Manganese (Mn^{2+}):** Plays a decisive role in the water oxidation system of photosystem II in photosynthesis.
- **Boron (B):** Its deficiency disrupts the transport of minerals and sugars.
- **Molybdenum (Mo^{6+}):** Essential for the functioning of nitrate reductase, a key enzyme in nitrogen metabolism.
- **Zinc (Zn^{2+}):** A crucial element for gene expression, as it helps maintain the structure of many transcription factors involved in regulating cellular gene expression.

Effect of mineral resource availability on growth:

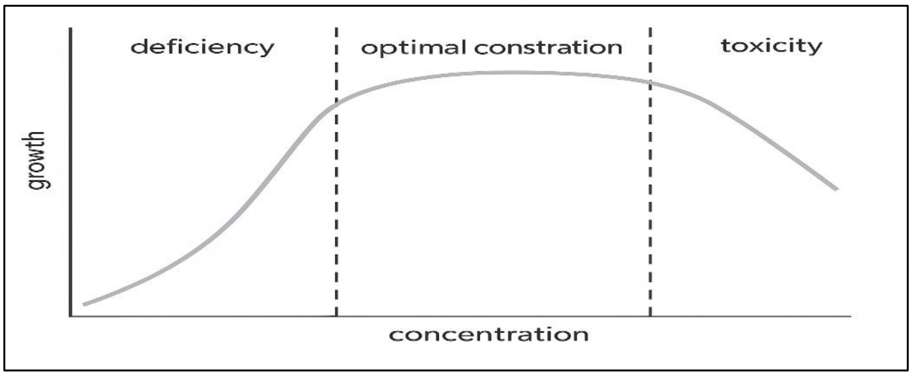

Figure 1 Influence of mineral element concentration on growth (Gaudy, 2012)

This curve shows an optimal plateau between deficiency at low concentrations and excess at high concentrations. Deficiency may result in nutrient shortages, while excess leads to toxicity.

Mineral deficiency manifests as growth limitation, resulting in reduced yields. In the ascending part of the curve, the element content in the environment is insufficient, causing a deficiency in plant tissues and restricting growth. At the plateau, the concentration is optimal; the minimum nutrient concentration that allows maximum growth is called the **critical point**, beyond this point, there is an increase in the element's concentration within the vacuole that does not contribute to growth; this is referred to as **luxury consumption**, at even higher nutrient doses, a slowdown in growth can occur, indicating **toxicity**.

Ion absorption by plants depends on several factors:

- The nature, availability, and interactions between ions in the soil;
- The soil's characteristics, such as the presence of charged colloids, its structure, pH, and temperature;
- The plant's age and physiological state, and the biological activity of the rhizosphere.

Slightly acidic soil solutions are generally favorable for ion absorption by plants. Conversely, an excess of calcium, by increasing soil alkalinity, can disrupt iron uptake in plants such as apple trees and grapevines. This prevents chlorophyll synthesis, leading to yellow spots on the leaves, a symptom known as iron chlorosis**.**

Passive and Active Transport

The movement of an ion from one compartment to another — for example, from the soil solution to the cytosol of a root hair, is called **passive transport** when it occurs in the direction of a decrease in the ion's concentration**.** In contrast, **active transport** takes place when the ion's concentration is higher in the destination compartment than in the original one. Active transport occurs against the concentration gradient and requires ATP as an energy source**.**

Different transport systems are found in the plasma membrane and the tonoplast (vacuolar membrane), such as: Ion pumps (H^+-ATPase and Ca^{2+}-ATPase pumps), Transporters and channels**,** Symport systems (e.g., $H^+ : NO_3^-$) and Antiport systems (e.g., H^+ / Na^+).

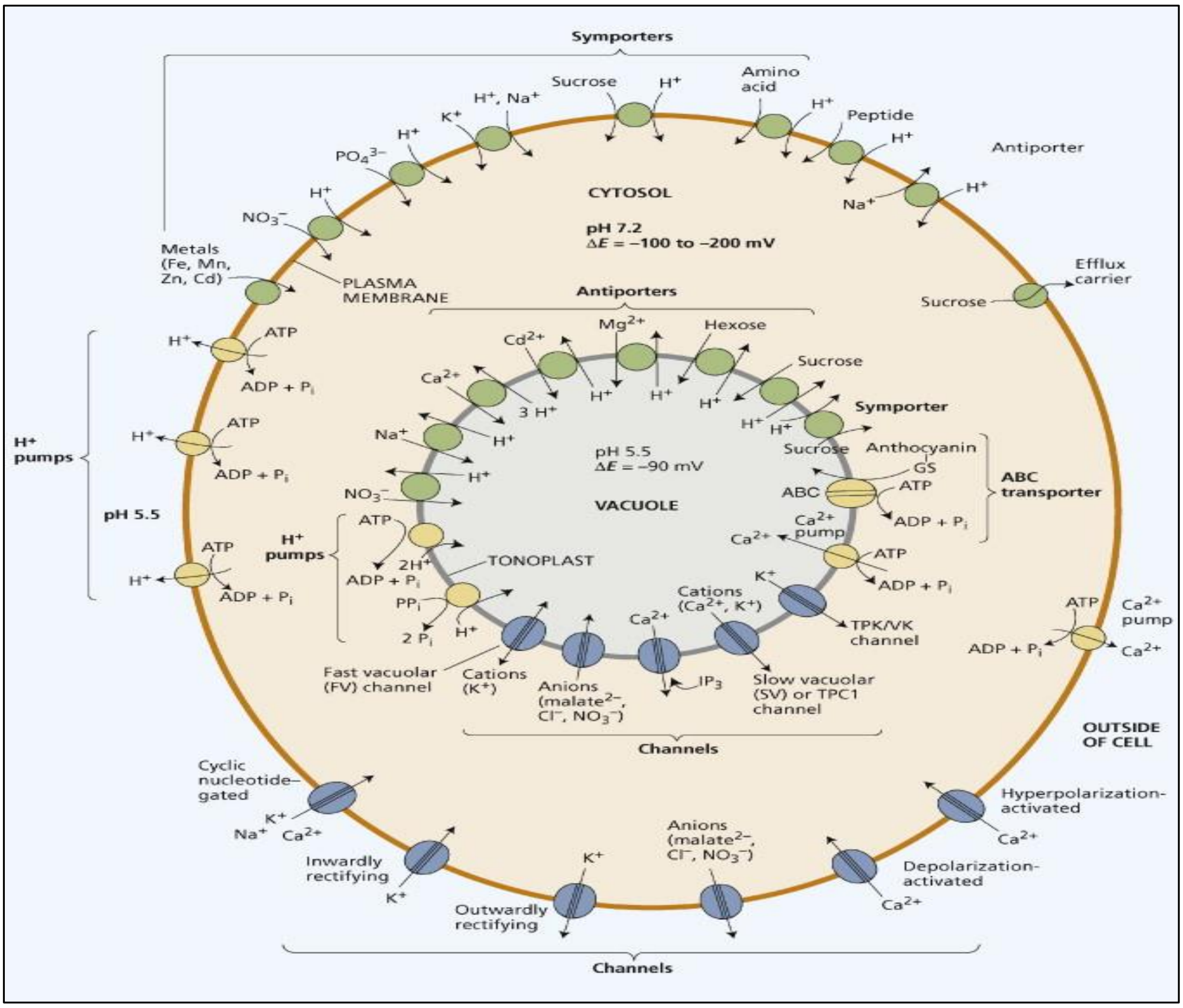

Figure 2 Main transport systems of the plasma membrane and the tonoplast