

**MINERALS IN SOIL AND FOOD: ORIGIN, AVAILABILITY, AND IDENTIFICATION
TECHNIQUES**

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Abstract

Mineral nutrients are inorganic substances essential for the growth, development, and maintenance of plants and humans. In the soil-plant system, the soil constitutes the main source of these elements, which are absorbed by the roots and incorporated into plant tissues, which then become food for animals and humans. Given this scenario, this chapter discusses and reviews relevant topics regarding mineral content. Minerals are classified into macronutrients, required in large quantities, such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, fundamental for plant growth. Micronutrients, such as iron, zinc, manganese, and copper, are needed in smaller quantities but are also essential because they act in metabolic processes and plant nutritional balance. However, the availability of these nutrients depends on factors such as organic matter, pH, moisture, texture, microbial activity, and others. Furthermore, adequate mineral nutrition in plants directly influences the composition of food and, consequently, human health. In this context, analytical techniques are essential for the determination and monitoring of minerals in the soil-plant-food system, contributing to sustainable management and nutritional quality.

Keywords: Plants, Nutrients, Analytical Techniques.

INTRODUCTION

Mineral nutrients are inorganic compounds essential for the growth, development, and maintenance of plants and human beings. In nature, they participate in biogeochemical cycles and are continuously reused within the food chain of living organisms (Farias; Silva; Andrade, 2022). It is the soil that supplies nutrients to plants, which later serve as food for animals and humans, thereby becoming integrated into the processes of growth and development of all living organisms (Farias; Silva; Andrade, 2022).

It may be stated that, in plants, these are classified as beneficial and essential nutrients. Nutrients recognized as beneficial are frequently found in plant tissues; although they are not indispensable to the life cycle of most plants, they can promote improvements in growth and development (Taiz; Zeiger, 2017; Batista et al., 2018). In addition, there are other elements present in plant tissues, defined as essential

nutrients; that is, they constitute an intrinsic component of the plant's structure or metabolism, or their absence causes severe anomalies in growth, development, and reproduction.

According to Taiz and Zeiger (2017), essential mineral elements can be defined as macro- and micronutrients, according to their concentration in plant tissue. Macronutrients are essential for plant growth and development and are required in large quantities. These nutrients—such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur—play fundamental roles in several plant biological functions. Essential micronutrients, in turn, are required in significantly lower quantities, such as iron, zinc, manganese, copper, among others; they play a fundamental role in metabolic processes and in maintaining plant health, as they participate in enzymatic reactions, nutritional balance, and the synthesis of compounds indispensable to plant development (Senila, 2024).

Along this line of reasoning, Sultanbawa and Sultanbawa (2023) describe soil as the principal natural medium that supplies minerals to plants. Among the seventeen nutrients defined and recognized as essential for plant growth, fourteen are obtained through soil: nitrogen, potassium, phosphorus, calcium, magnesium, iron, zinc, copper, manganese, sulfur, chlorine, boron, molybdenum, and nickel. Such nutrients are absorbed by plants through biological mechanisms such as roots, and plants, in turn, enrich foods of plant origin.

Once absorbed into plant tissues, these minerals become available for dietary consumption and, when present in a balanced manner in the diet, they come to perform relevant functions in human metabolism—acting in the regulation and maintenance of cellular activity, the transport of various substances, the maintenance of muscular and nervous activity, the facilitation of compound transfer across cell membranes, and the composition of organic tissues—while also being indirectly involved in numerous metabolic processes (Grillo et al., 2020).

However, the mineral composition of plants may be influenced by numerous factors, including genetic variability among plant species, the cultivation environment, management practices, organic

matter content, conditions such as pH, soil moisture, aeration, as well as soil microbial diversity, among others (Sultanbawa; Sultanbawa, 2023).

In this context, the quantitative determination of mineral compounds throughout the soil–plant–food product system becomes fundamental, with the aim of providing a detailed analysis of mineral content and the necessary adjustments. Currently, different analytical techniques are available, such as Atomic Absorption Spectrophotometry (AAS), Flame Atomic Absorption Spectrometry (FAAS), Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES), and Inductively Coupled Plasma Mass Spectrometry (ICP MS), among other techniques focused on precision, broad applicability, and automation (HE et al., 2024).

RESULTS AND DISCUSSION

MINERALS IN SOIL

Soil is the principal medium for plant development, acting as physical support, a nutrient source, and a water reservoir. Its formation results from the actions of physical, chemical, and/or biological weathering on rocks and organic materials. Simultaneously, soil formation is influenced by several factors, such as parent material, climate, biological activity, vegetation, and relief, in addition to the duration of these processes. The interaction among these factors is responsible for soil formation and evolution over the years, determining properties that directly influence its fertility, structure, and capacity to sustain plant growth (Batista et al., 2018; Cordovil et al., 2025).

Soil is a heterogeneous, three-phase system composed of solid, liquid, and gaseous phases, which coexist and interact dynamically and are fundamental to the availability of water, nutrients, and oxygen to plants. In most soils, the solid phase is predominantly formed by minerals, which generally represent 45% or more of the composition, whereas organic matter corresponds to a smaller fraction, typically up to about 5%. The liquid and gaseous phases occupy soil pores, which may represent approximately 50% of total soil volume (Leite; Zeimath; Herrmann, 2005; Xavier, 2018).

In this context, knowledge of soil composition is fundamental, especially that of the liquid phase—commonly referred to as the soil solution—because it consists of the water present in soil pores in which mineral elements available to plants are dissolved. Through the soil solution, plants absorb water via their roots and, together with it, essential and beneficial nutrients indispensable to plant growth and development (Souza et al., 2013).

The chemical characterization of a soil evidences the presence of numerous elements and, similarly, the occurrence of these same elements in the composition of plant tissues. Any constituent in available form can be absorbed by plants; however, mere presence in plant tissue does not indicate that it is indispensable to plant nutrition. Therefore, it becomes necessary to distinguish elements essential to plant growth and development from those which, although not essential, may exert beneficial effects on plants (Mendes, 2007).

The criteria of Arnon and Stout (1939) define the essentiality of a nutrient based on the plant's inability to complete its life cycle in its absence, the impossibility of substituting that element with another to correct deficiency symptoms, and its direct metabolic role—excluding indirect effects such as improvements in the soil's physicochemical properties. From this perspective, when plants have these elements, together with water and solar energy, they are capable of synthesizing all compounds necessary for normal development.

It is important to note that, among essential elements, hydrogen, carbon, and oxygen are not classified as mineral nutrients, because they are obtained primarily from water and carbon dioxide, and not from the mineral fraction of soil. Essential mineral nutrients are, in turn, subdivided into macronutrients and micronutrients, according to the quantities in which they are required and absorbed by plants (Ronquim, 2020).

Macronutrients

Macronutrients are elements required in greater quantities compared to other nutrients. Among them, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) stand out, as they play fundamental roles in various biological functions in plants.

Nitrogen

From a quantitative standpoint, nitrogen (N) is one of the most important nutrients for agricultural crops, frequently constituting the main limiting factor in diverse production systems. In plants, it plays a fundamental role in plant metabolism by integrating the structure of essential compounds for development. Among these metabolites are amino acids, proteins, enzymes, coenzymes, nucleic acids, pigments, lipoproteins, and vitamins (Forghieri et al., 2026).

The forms of nitrogen preferentially absorbed by plants are nitrate (NO_3^-) and ammonium (NH_4^+). The contact of these ions with roots occurs mainly through mass flow, a process in which nutrients are transported together with the water moving from the soil toward the root system (Batista et al., 2018).

The principal source of N is the atmosphere (N_2), a gaseous form that is chemically inert and unavailable to plant metabolism, requiring reduction in order to be assimilated by plants. The transfer of atmospheric nitrogen to soil occurs through fixation mechanisms, such as electrical discharges. However, the most significant pathway is Biological Nitrogen Fixation (BNF), a process mediated by diazotrophic microorganisms that convert N_2 into forms assimilable by plants. It is estimated that BNF is responsible for approximately 92% of all nitrogen fixed annually (Batista et al., 2018; Costa, 2023).

Another form of supplying the soil–plant system may occur through mineral fertilizers, which make the nutrient immediately available, as well as through organic sources, such as manures and composts. As highlighted by Malavolta (2006), nitrogen-use efficiency is directly related to the appropriate choice of source and to management synchronized with plant demand, considering the high mobility and constant transformations of this nutrient in the biogeochemical cycle.

Phosphorus

Phosphorus (P) is part of the constitution of various organic compounds and is essential for reproduction and cell division, playing a fundamental and irreplaceable role in plant metabolism. It acts as a structural element and participates directly in energy storage and transfer. It is present in the form of phosphate esters and integrates essential molecules such as DNA and RNA, as well as energetic compounds such as adenosine triphosphate (ATP) and adenosine diphosphate (ADP). Its action is indispensable in several metabolic processes vital to plant maintenance and full functioning (Anghinoni; Bissani, 2004; Sasabuchi et al., 2023).

In the soil system, phosphorus exhibits complex dynamics and occurs in different fractions, being present in both soluble and insoluble forms. It is distributed among the soil solution (readily assimilable form), the organic fraction, and insoluble mineral forms. Soluble forms, generally inorganic in nature, are characterized by the presence of free orthophosphate ions such as PO_4^{3-} , HPO_4^{2-} , and H_2PO_4^- , which constitute the main chemical species absorbed by plants and, therefore, represent the forms directly available in the soil solution (Sasabuchi et al., 2023; Souza et al., 2013).

Phosphate fertilization constitutes an important tool to meet plants' nutritional requirements and ensure adequate development and good crop yields. Phosphate fertilizers can be classified into natural phosphates, thermophosphates, partially acidulated phosphates, and soluble phosphates (Anghinoni; Bissani, 2004). The choice of the most appropriate source is fundamental and should consider factors such as soil type, pH, phosphorus adsorption capacity, the crop to be established, and the management system adopted.

Potassium

In plants, potassium (K) is present in quantities similar to nitrogen. In plant species, it occurs abundantly in the cytoplasm and chloroplast, exerting essential regulatory functions and acting as an

activator of various enzymes. It is also linked to several photosynthetic processes and participates in ATP formation (Meurer; Inda, 2004).

Potassium fertilization consists of applying potassium-rich sources to meet the high demand of crops. In soil, potassium is found mainly in the form of the K^+ cation, and its availability is influenced by Cation Exchange Capacity (CEC) and by clay mineralogy; it may undergo losses by leaching due to its high mobility. The main mineral source used is potassium chloride (KCl), although sources such as potassium sulfate and potassium nitrate may also be used (Otto; Vitti; Luz, 2010).

Calcium

Present in high concentrations in soil, calcium (Ca) is absorbed by plants in the form of the Ca^{2+} ion. This nutrient participates in the formation of organic compounds such as oxalates, citrates, and tartrates, in addition to exerting fundamental structural and physiological functions. It is indispensable for the formation of the middle lamella of the cell wall, conferring stability and integrity to plant tissues, and plays an important role in the absorption, transport, and balance of other nutrients within the plant (Anghinoni; Bissani, 2004).

Limestone constitutes the principal calcium source for the soil–plant system, simultaneously serving as a fertilizer and a soil acidity corrector by raising pH and neutralizing toxic aluminum. Through liming, calcium carbonate ($CaCO_3$) reacts with moisture and hydrogen ions in soil, promoting their neutralization and releasing the Ca^{2+} cation to the exchange complex. Another alternative calcium source is agricultural gypsum ($CaSO_4$), which, in addition to supplying Ca^{2+} , also provides sulfur to the system and contributes to improving chemical conditions in subsurface soil layers (Costa et al., 2011).

Magnesium

In plant cells, magnesium (Mg) plays a fundamental role in activating several enzymes involved in processes such as respiration, photosynthesis, and carbon incorporation. It also plays an important role in

plant defense mechanisms under abiotic stress conditions (Senbayram et al., 2015). In addition, magnesium is a structural component of the chlorophyll molecule, which underscores its direct importance in capturing light energy and carrying out photosynthesis (Castro et al., 2020; Taiz; Zeiger, 2013).

In general, Brazilian soils present low magnesium contents. This nutrient originates from the weathering of rocks containing primary minerals, as well as some secondary minerals. After being released into the soil solution, Mg^{2+} may follow different pathways: it may be leached along the profile, adsorbed to the cation exchange complex, precipitated as minerals, lost by erosion, or absorbed by plants (Batista et al., 2018; Castro et al., 2020).

Sulfur

Sulfur (S) is present in the composition of sulfur-containing amino acids such as cystine, cysteine, and methionine, and it also integrates several coenzymes and vitamins, including coenzyme A, S-adenosylmethionine, biotin, vitamin B₁, and pantothenic acid. These compounds play essential functions in plant metabolism, participating in biochemical reactions fundamental to growth, protein synthesis, and proper cellular functioning (Taiz; Zeiger, 2013).

Sulfur dynamics in soil are characterized by a series of chemical and biological processes, including redox reactions, mineralization and immobilization of organic matter, as well as adsorption and desorption of sulfates on soil colloids—factors that directly influence its availability to plants (Teixeira et al., 2017). It is found predominantly in organic form; thus, the supply of this nutrient to plants is directly related to organic matter content and its mineralization. This process gradually releases sulfur as sulfate (SO_4^{2-}) into the soil solution, enabling root uptake. However, the immediate availability of S is regulated by the balance between sulfate adsorption and desorption processes in the solid phase and its concentration in the soil solution, as described by Anghinoni and Bissani (2004).

Micronutrients

Essential micronutrients are required in significantly lower quantities. Taiz and Zeiger (2017) describe the main micronutrients and their activities in plant metabolism as: iron (Fe), which is fundamental for chlorophyll synthesis and cellular respiration; manganese (Mn), which assists in photosynthesis and protection against oxidative stress; zinc (Zn), essential for cell growth and protein synthesis; copper (Cu), which participates in photosynthesis and protects against diseases; boron (B), crucial for cell formation and sugar transport; molybdenum (Mo), important for nitrogen fixation and protein synthesis; and chlorine (Cl), which assists in osmotic balance and photosynthesis. Deficiency or imbalance of these micronutrients can impair plant growth, compromising crop productivity and quality (Senila, 2024).

Soils exhibit significant variations regarding micronutrient content, and their amounts may vary according to levels present in parent materials. These micronutrients may integrate the internal structure of minerals or be adsorbed onto the surface of minerals and organic compounds (Bohnen; Bissani, 2004; Matos et al., 2024).

Micronutrient sources used in agriculture are widely described in national and international literature and, in general, are classified into inorganic sources (such as salts, acids, oxides, and oxysulfates), organic sources (synthetic chelates and organic complexes), and silicated oxides. The choice of source and application method should take into account points such as the area's history, soil analysis, visual diagnosis and/or leaf analysis. Micronutrients can be supplied via seed treatment—such as the application of molybdenum (Mo) and cobalt (Co), used to improve BNF; via soil, in the seeding furrow or incorporated into the soil; and via foliar application, which provides rapid and efficient availability, provided that highly soluble sources are used (Vitti; Grando, 2005).

SOIL MINERALS AND PLANT NUTRITION

In view of soil mineral composition, the mineral content of foods of plant origin shows a direct dependence on the availability of minerals present in the soil, the plant's capacity to absorb them, and the translocation of minerals to edible tissues such as leaves, fruits, seeds, and even roots. Therefore, it can be stated that soil, plants, food, and humans are interrelated; and, due to these conditions, the presence of a large quantity of minerals in the soil does not guarantee that they will be available to plants, nor does it guarantee proper plant growth and development (Sultanbawa; Sultanbawa, 2023).

For minerals to be effectively available, certain factors are indispensable, such as soil pH, the organic matter present, texture, among others. pH controls mineral solubility, the chemical forms in which minerals occur, and their interaction with organic matter. An acidic pH increases the availability of iron, magnesium, zinc, and copper, whereas a neutral or slightly acidic pH is considered ideal for crops; an alkaline pH disfavors mineral availability and may cause calcium precipitation.

In the case of organic matter, its role ends up being that of a fertility regulator: it forms complexes with minerals, prevents leaching, and also improves water retention as well as soil structure. Soil texture, in turn, interferes in aspects such as water retention, nutrient retention, and soil aeration (Barrow; Hartemink, 2023; Jindo et al., 2023; Maluf et al., 2015).

Mineral absorption effectively occurs in plant roots, which make minerals available, in the region called the root hair zone, where root hairs are located, providing a larger contact area with the soil solution. Thus, for nutrients to be absorbed, they must be in their soluble ionic form (Alaoui, 2022).

The transport of minerals to the root surface occurs in three ways: mass flow, diffusion, and root interception. In mass flow, water serves as the transport medium for nutrients. Diffusion operates by the migration of nutrients from a more concentrated region to a less concentrated region, whereas in root interception the root grows and comes into direct contact with nutrients present in the soil, though it provides a smaller quantitative contribution (Alaoui, 2022).

After nutrient absorption, the process of translocation occurs, whereby these minerals are distributed to different plant tissues; this can occur via the xylem and the phloem. The xylem transports minerals to the aerial parts of plants in a unidirectional flow, and the main nutrients transported by it are calcium, magnesium, nitrate, and sulfate. In contrast, the phloem exhibits bidirectional flow, transporting nutrients such as phosphorus, potassium, zinc, among others, to other plant parts such as fruits, seeds, and storage organs. Translocation determines how much nutrients will reach the edible parts of foods (Dalir, 2023; Le Bot; Adamowicz; Robin, 1998).

MINERALS IN FOODS

Minerals present in foods result from plants' ability to absorb nutrients from soil, mainly through roots, and incorporate them into their tissues. Thus, the mineral quality of foods depends on the plant's capacity to capture and distribute these elements throughout its development (Saloner; Bernstein, 2023). However, the bioavailability of these minerals for absorption by the human body is influenced by inhibitors present in the plant matrix, such as phytates and fibers, which may bind to ions such as zinc and calcium, limiting their intestinal absorption (Balaji et al., 2026).

With the aim of increasing agricultural productivity and enhancing the availability of micro- and macronutrients in soil, fertilizers are used. However, their inadequate application can compromise soil quality, affect natural resources, and generate impacts on human health, making balanced nutritional management essential (Bana et al., 2022). According to the study by Bana et al. (2022), application of a multielement foliar fertilizer improved nutritional quality in eggplant fruits, with significant increases observed in concentrations of Fe (+26%), Zn (+34%), K (+6%), Cu (+24%), and Mn (+27%), minerals fundamental to the functioning of the human body.

These minerals are nutrients indispensable for maintaining physiological functions and must necessarily be obtained through diet, since the human body is not able to synthesize them (Guardia; Garrigues, 2015). Different mineral ions perform specific and crucial biological functions. For example,

insufficient zinc, selenium, and iron can significantly impair immune responses and increase susceptibility to infections (Gombart; Pierre; Maggini, 2020). In addition, potassium and magnesium play fundamental roles in regulating blood pressure and heart rhythm, such that deficiency of these elements is associated with a higher risk of developing hypertension and cardiovascular diseases (Razzaque; Wimalawansa, 2025). Thus, the mineral composition of foods is determined by interactions among soil, agricultural management practices, and plant metabolism, directly influencing the nutritional quality of the diet and its relationship to human health (Morton et al., 2023).

MINERAL ANALYSIS

Currently, an indispensable factor is the determination of mineral elements in diverse analytes. Because of their biochemical action in living organisms, low levels and/or the absence of certain metals may cause complications—from plants to humans—just as elevated concentrations may negatively affect them (Senila, 2024). In this manner, metal content can be analyzed by analytical techniques such as AAS, FAAS, ICP-OES, ICP-MS, and many others (HE et al., 2024).

Spectrometric techniques provide information about the chemical composition of substances through the principles of spectroscopy—namely, through the interaction between electromagnetic radiation and matter (Rawat et al., 2024). Among these techniques, AAS is one of the most widely used, based on the absorption of specific wavelengths of light by atoms in the gaseous state. The emitted light is absorbed by the analytes, quantified, and thus enables the identification and quantification of specific elements. AAS presents advantages in the analysis of metals and metalloids in diverse matrices. In FAAS, the technique is also based on the absorption of specific wavelengths by atoms in the gaseous state, wherein atomization is carried out by a flame (Rawat et al., 2024).

ICP-OES and ICP-MS techniques offer high sensitivity, selectivity, and accuracy and are based on the use of a high-temperature plasma generated from argon gas for sample atomization, excitation, and ionization. Whereas ICP-OES quantifies the light emitted at specific wavelengths by analytes, ICP-MS

focuses on the mass-to-charge ratio of ions, enabling the determination of elemental concentrations (Naozuka, 2025). In addition, ICP-MS has the further advantage of identifying more than one element present in the sample, with a wide linear range, high accuracy, sensitivity, selectivity, and low detection limits (HE et al., 2024).

A crucial step in any analytical technique is sample preparation. If it is not performed correctly and appropriately, results may be accompanied by errors, rendering the analysis problematic and unreliable (Assis et al., 2024). The main stages of sample preparation involve: collection, storage, homogenization, and digestion; however, the specificities depend on each sample type, such as soil, water, and biological or food matrices. Adequate sample preparation is essential for analyses because it fragments and solubilizes the matrix, makes metals available for analysis, extracts metals of interest from the matrix into an appropriate solvent, concentrates metals present at low concentrations, eliminates interferences, and reduces matrix effects (Rawat et al., 2024).

CONCLUSION

This review highlighted the role of mineral nutrients in maintaining soil fertility, in plant development, and, consequently, in the nutritional quality of foods. It can be concluded that the dynamics of macro- and micronutrients in the soil–plant system result from interdependent physical, chemical, and biological processes that determine their availability, absorption, and use by plants. Moreover, the mechanisms that regulate the mobility, transformation, and interaction of minerals in soil make it possible to improve nutritional management strategies, promoting greater efficiency in fertilizer use and sustainability of production systems.

Analogously, adequate mineral nutrition of plants directly reflects in the mineral composition of foods, establishing a direct connection among soil quality, agricultural productivity, and human health. Therefore, mineral analysis constitutes an indispensable tool for nutritional diagnosis and for technical

decision-making, enabling the assessment of deficiencies, excesses, and imbalances, thereby contributing to more sustainable and safer agricultural practices.

In this context, integrated study of minerals in soil, plants, and foods reinforces the importance of a systemic approach, in which fertility, plant nutrition, and food quality are not isolated topics, but rather parts of a continuous process that sustains agricultural production and food security.

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