

CASSIO PEREIRA HONDA FILHO

Soil fertility management and mineral nutrition in coffee farming



EDITORA
SCHREIBEN



CASSIO PEREIRA HONDA FILHO

Soil fertility management and mineral nutrition in coffee farming



EDITORA
SCHREIBEN

2025

© Cassio Pereira Honda Filho - 2025
Editing and Cover: Schreiben
Cover Image: ALEXSTUDIO - Freepik.com
Revision and Translation: the author
Book published on: 09/29/2025
Publication Term: TP0902025

Editorial Board (Schreiben Publishing)::

Dr. Adelar Heinsfeld (UPF)
Dr. Airtton Spies (EPAGRI)
Dra. Ana Carolina Martins da Silva (UERGS)
Dr. Cleber Duarte Coelho (UFSC)
Dr. Daniel Marcelo Loponte (CONICET – Argentina)
Dr. Deivid Alex dos Santos (UEL)
Dr. Douglas Orestes Franzen (UCEFF)
Dr. Eduardo Ramón Palermo López (MPR - Uruguai)
Dr. Fábio Antônio Gabriel (SEED/PR)
Dra. Geuciane Felipe Guerim Fernandes (UENP)
Dra. Ivânia Campigotto Aquino (UPF)
Dr. João Carlos Tedesco (UPF)
Dr. Joel Cardoso da Silva (UFPA)
Dr. José Antonio Ribeiro de Moura (FEEVALE)
Dr. Klebson Souza Santos (UEFS)
Dr. Leandro Hahn (UNIARP)
Dr. Leandro Mayer (SED-SC)
Dra. Marcela Mary José da Silva (UFRB)
Dra. Marciane Kessler (URI)
Dr. Marcos Pereira dos Santos (FAQ)
Dra. Natércia de Andrade Lopes Neta (UNEAL)
Dr. Odair Neitzel (UFFS)
Dr. Waniilton Dudek (UNESPAR)

This publication is an independent production. The accuracy of the information, opinions, and concepts expressed herein, as well as the origin and presentation of tables, charts, maps, photographs, and references, is the sole responsibility of the author(s).

Editora Schreiben
Linha Cordilheira - SC-163
89896-000 Itapiranga/SC
Tel: (49) 3678 7254
editoraschreiben@gmail.com
www.editoraschreiben.com

International Standard Cataloging-in-Publication Data (CIP)

H771 Honda Filho, Cassio Pereira.
Soil fertility management and mineral nutrition in coffee farming / Cassio Pereira Honda Filho. – Itapiranga, SC : Schreiben, 2025.
80 p. ; e-book.
Inclui bibliografia e índice remissivo
E-book no formato PDF.
ISBN: 978-65-5440-520-1
DOI: 10.29327/5674937
1. Cafeicultura - Fertilizantes e adubação. 2. Fertilidade do solo.
3. Nutrição mineral de plantas. 4. Café (Planta) - Nutrição. I. Título.

CDD 633.738

Responsible Librarian Juliane Steffen CRB14/1736

SUMMARY

CHAPTER 1

INTRODUCTION TO SOIL FERTILITY IN COFFEE FARMING.....5

CHAPTER 2

ESSENTIAL MACRONUTRIENTS FOR COFFEE.....9

CHAPTER 3

MICRONUTRIENTS AND

THEIR PHYSIOLOGICAL ROLE IN COFFEE GROWING.....17

CHAPTER 4

NUTRIENT DYNAMICS IN THE SOIL PROFILE AND THE

INFLUENCE OF PHYSICAL AND CHEMICAL PROPERTIES.....27

CHAPTER 5

METHODS FOR DIAGNOSING SOIL FERTILITY

AND THE NUTRITIONAL STATUS OF COFFEE TREES.....35

CHAPTER 6

LIME AND GYPSUM PRACTICES IN COFFEE FARMING:

EFFECTS AND RECOMMENDATIONS.....39

CHAPTER 7

ORGANIC MATTER AND

CARBON MANAGEMENT IN COFFEE FARMING SOILS.....47

CHAPTER 8

MINERAL NUTRITION AND

ITS EFFECTS ON COFFEE QUALITY.....53

CHAPTER 9

TECHNICAL AND PRACTICAL FERTILIZATION

RECOMMENDATIONS FOR COFFEE TREES.....57

CHAPTER 10

FUTURE CHALLENGES AND INNOVATIONS IN FERTILITY AND NUTRITION IN COFFEE FARMING.....	65
FINAL CONSIDERATIONS.....	69
ACKNOWLEDGMENTS.....	71
REFERENCES.....	73

INTRODUCTION TO SOIL FERTILITY IN COFFEE FARMING

Coffee cultivation in Brazil emerged as a prominent agricultural activity in the 19th century, consolidating itself as one of the country's main export products. However, most of the soils initially used were naturally low in fertility or were quickly depleted by rudimentary agricultural practices. The lack of technical knowledge at the time resulted in the adoption of empirical methods such as fallow, crop succession, and sporadic use of animal manure, which, although minimally effective, were not sufficient to sustain high levels of productivity over time. The situation began to change with the advancement of soil science in Brazil, especially in the second half of the 20th century, when institutions dedicated to the systematic study of fertility and proper management of agricultural soils emerged.

It was with the creation of the Brazilian Soil Science Society, the consolidation of the Campinas Agronomic Institute (IAC), and later with the strengthening of Embrapa Solos and Embrapa Café, that the country began to have a technical and scientific body capable of supporting the transition from traditional coffee farming to technified agriculture. The founding of Embrapa in 1973 represents a watershed moment in this process. From then on, recommendations on fertilization, acidity correction, use of limestone and agricultural gypsum, as well as the management of macro and micronutrients, began to be based on experimental evidence and published in technical bulletins and field manuals. The Coffee Manual and the documents of the Coffee Research Consortium have become national references in fertility management, guiding producers on good practices that combine science and agronomic efficiency.

In recent decades, a new approach has gained prominence: the so-called “soil fertility building.” Unlike isolated corrective management, this strategy involves preparing the edaphic environment in advance so that the coffee tree can develop under ideal conditions from the moment the crop is planted. This involves the careful application of corrective agents and fertilizers, the incorporation of organic matter, the adoption of cover crops such as *brachiaria* between rows, and strict observance of the so-called 4Cs: the right amount, the right time, the right place, and the right source of nutrients. By proposing this integrated view, researchers such as Reis, Guimarães, and Oliveira have contributed to consolidating a production model that combines efficiency and sustainability.

Understanding soil fertility as a multidimensional concept has, in turn, led to a growing appreciation of soil physical quality. Studies on aggregation, porosity, density, and water infiltration have shown that soil structure directly influences nutrient dynamics and root growth in coffee plants. For this reason, conservation practices such as deep mechanical decompaction, minimum tillage, the use of cover crops, and mulch maintenance have become part of the technological package of modern coffee farming.

This approach allows for greater use of applied fertilizers, reduces losses due to leaching, and improves the physiological performance of the plant. Organic matter has come to be understood as a central element of fertility, not only for its direct chemical effects, such as increasing CTC, gradually releasing nutrients, and complexing toxic metals, but also for its physical and biological functions.

It improves water retention, promotes microbial activity, and contributes to soil structure stability. Recent research conducted in the Mogiana region of São Paulo, for example, has shown that intensively managed coffee crops have lower organic carbon content and greater structural degradation when compared to areas with perennial cover or native vegetation. This reinforces the importance of organic matter not only as an agronomic input but also as an indicator of sustainability.

Periodic monitoring of fertility has become an integral part of the technified coffee growing calendar. It is recommended that soil analysis be carried out after harvest, in July and August, allowing the fertilization

plan to be adjusted according to losses caused by production. These adjustments are made based on classic fertility principles, such as the Law of the Minimum, which states that the most limiting nutrient is the one that determines productivity, and the Law of Diminishing Increases, according to which successive increases in fertilization tend to generate progressively lower returns. By integrating these concepts with local data and laboratory analyses, producers reduce costs and environmental impacts without compromising crop yields.

A recent advance in soil fertility studies in coffee trees was the ClimapestFACE (Free Air Carbon-Dioxide Enrichment) experiment, conducted by Embrapa Meio Ambiente, which simulated an increase in atmospheric CO₂ concentration in crops with brachiaria grass between rows. The results showed a reduction in available phosphorus and changes in potassium dynamics, highlighting the need for adjustments in fertilizer management in the face of climate change. These findings confirm the dynamic nature of soil fertility, which is influenced by edaphic and climatic factors and the cropping system.

Soil fertility in Brazilian coffee farming is sustained by three pillars: chemical (pH, macro and micronutrients), physical (structure, porosity, water retention, and compaction), and biological (organic matter, microbial activity, and nutrient cycling). Studies conducted in Muzambinho (MG) have shown that shaded crops have better chemical balance and greater physical stability compared to those grown in full sun. Shading helps regulate soil temperature and reduce evaporation, favoring the edaphic microclimate, microbial activity, and nutrient availability. In addition, the adoption of grasses as cover between rows promotes the formation of macropores and micropores, increasing organic matter and nutrient cycling, strengthening the physical-chemical and biological attributes of the soil. Considering that many coffee soils in Brazil are naturally acidic and low in fertility, practices such as liming, balanced fertilization, and deep profile management are essential to maintain and improve these three pillars in a sustainable manner.

National scientific production has been strengthening this integrated approach. Recent studies address, for example, the effects of different sources and doses of phosphorus on the initial development

of coffee trees, the impacts of simultaneous extraction of cations with different extractive solutions, and the use of organomineral fertilizers as a promising alternative for nutritional balance in nurseries and newly planted areas. The combination of experimental data, economic analyses, and environmental sustainability indicators has been valued as a criterion for validating new technologies.

Thus, the history of soil fertility studies in Brazilian coffee farming shows a trajectory of profound technical and scientific evolution. Starting from empirical practices, progress was made toward methods based on diagnosis, prognosis, and monitoring, culminating in management models that combine high productivity, conservation of natural resources, and mitigation of environmental impacts. The success of this trajectory is largely due to the continuous research and extension work of institutions such as Embrapa, IAC, federal and state universities, cooperatives, and companies in the productive sector. In view of the challenges posed by agricultural intensification and climate change, it is imperative to maintain investment in soil science, valuing fertility as the basis for resilient and sustainable production systems.

ESSENTIAL MACRONUTRIENTS FOR COFFEE

Mineral nutrition is one of the pillars of coffee productivity. The coffee plant requires large amounts of nutrients, especially during vegetative growth, formation, and filling of beans. Among the essential elements, macronutrients are required in larger quantities and play fundamental physiological roles in vegetative structures, metabolism, and reproduction. In commercial crops, macronutrient deficiencies impair vegetative development, stress resistance, and bean quality and yield.

In modern coffee farming, macronutrient nutrition is based on diagnostics such as soil and leaf tissue analysis, as well as strategic fertilizer application according to plant demand, soil nutrient dynamics, and losses due to leaching or volatilization.

1. NITROGEN (N)

Functions in the coffee plant

Nitrogen is the nutrient most required by the coffee plant, playing a fundamental role in the construction of cell structures and energy metabolism. It composes amino acids, proteins, enzymes, nucleic acids (DNA and RNA), and nucleotides such as ATP and NADPH, and is also an essential element of the chlorophyll molecule. Its presence directly influences the rate of net photosynthesis, promoting greater biomass accumulation, root development, and leaf expansion. In coffee plants, nitrogen stimulates the emission of orthotropic and plagiotropic branches, giving the canopy a balanced architecture and favoring light interception. In addition, it is associated with the regulation of genes related to senescence, contributing to the functional longevity of leaves, which directly affects yield in successive flushes.

Symptoms of deficiency

- Generalized chlorosis in older leaves, with uniform yellowing.
- Reduced plant growth and shortening of internodes.
- Significant reduction in fruit production and quality.

Common sources of fertilization

- Urea (45% N)
- Ammonium nitrate (33% N)
- Ammonium sulfate (21% N)
- Organic sources: vegetable cakes, organic compounds, cured manure.

2. PHOSPHORUS (P)

Functions in the coffee plant

Phosphorus is essential for energy metabolism and biochemical processes vital to the physiology of the coffee plant. It is a component of ATP, NADP⁺, coenzymes, and nucleic acids, and is essential for cell division and the growth of meristematic tissues. Its adequate presence favors the development of the root system, especially the lateral roots, which ensure better absorption of water and nutrients.

Symptoms of deficiency

- Delayed growth, especially of the roots.
- Blue-green leaves with a purplish hue at the edges.
- Delayed flowering and reduced fruit set.
- Reduced production.

Common sources of fertilization

- Simple superphosphate (18% P₂O₅)
- Triple superphosphate (41-45% P₂O₅)
- Reactive natural phosphate (depending on pH and remaining P)
- MAP – Monoammonium phosphate (11% N; 52% P₂O₅)

3. POTASSIUM (K)

Functions in the coffee plant

Although potassium is not a component of the plant's organic structures, it is crucial for cellular functionality in coffee trees. It acts as an activator of dozens of enzyme systems, participates in the regulation of cellular osmotic potential, and plays a central role in controlling stomatal opening and closing, directly influencing transpiration and water use efficiency. In metabolism, it contributes to the translocation of photoassimilates, facilitating the transport of carbohydrates from vegetative tissues to fruits, an essential process for uniform grain filling and synchronization of maturation. Under adverse conditions, potassium helps maintain turgor and tolerance to water stress and salinity, in addition to reducing the coffee tree's susceptibility to leaf diseases, such as cercosporiosis. It is also involved in the metabolism of sugars and phenolic compounds, which can influence attributes related to beverage quality.

Deficiency symptoms

- Marginal chlorosis on older leaves, followed by necrosis.
- Malformed and shriveled beans.
- Premature leaf and fruit drop.

Common sources of fertilization

- Potassium chloride (60% K₂O)
- Potassium sulfate (50% K₂O and 17% S)
- Potassium nitrate (13% N and 44% K₂O)
- Plant ash (in agroecological crops)

4. CALCIUM (Ca)

Functions in the coffee plant

Calcium is a structural nutrient of high importance for coffee trees, composing the middle lamellae of cell walls in the form of calcium pectate, which gives rigidity and cohesion to plant tissues. It also acts as a second

intracellular messenger in growth and defense processes, participating in the regulation of gene expression and signaling between organelles. Its availability is essential for the development of apical and floral buds, ensuring the continuity of vegetative and reproductive growth. In addition, calcium stabilizes plasma membranes and modulates the activity of various enzymes, promoting greater tolerance to ionic imbalances and aluminum toxicity in acidic soils. Adequate calcium levels are associated with root system integrity and increased flower and fruit set, contributing to coffee tree productivity and longevity.

Deficiency symptoms

- Necrosis and death of the apical meristem (buds).
- Deformed, thick, and chlorotic young leaves.
- Root system with stunted growth.
- Reduced flowering and increased fruit drop.

Common sources of fertilization

- Dolomitic or calcitic limestone
- Agricultural gypsum (also a source of sulfur)
- Calcium nitrate (15.5% N and 19% Ca)
- Araxá phosphate (with secondary Ca content)

5. MAGNESIUM (Mg)

Functions in the coffee plant

Magnesium is closely linked to photosynthesis in coffee trees, as it is the central atom of the chlorophyll molecule and is essential for light absorption and atmospheric carbon fixation. It acts as a cofactor for several enzymes involved in phosphate transfer, carbohydrate synthesis, and nucleic acid metabolism. It is essential for the activation of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), the main enzyme in the Calvin cycle, and participates in the transport of sucrose, the main photoassimilate directed to developing fruits. In coffee plants, magnesium has high mobility in the phloem, allowing the redistribution of nutrients

to organs with higher demand, especially during fruiting. Adequate magnesium nutrition prevents nutritional imbalances, especially with potassium and calcium, and contributes to the formation of grains with better accumulation of sugars and quality compounds, potentially raising the sensory standard of the beverage.

Symptoms of deficiency

- Internerval chlorosis in older leaves.
- Marginal necrosis and early leaf fall in severe cases.
- Reduction in photosynthetic rate and vegetative vigor.

Common sources of fertilization

- Magnesium sulfate (9% Mg and 13% S).
- Dolomitic limestone (in liming).
- Magnesium thermophosphates.
- Specific foliar fertilizers (chelated Mg, sulfate, nitrate, concentrated suspension).

6. SULFUR (S)

Functions in the coffee plant

Sulfur plays essential roles in the biochemistry of coffee, integrating sulfur amino acids such as cysteine and methionine and participating in the composition of vitamins such as thiamine (B₁) and biotin. It is essential for the three-dimensional conformation of proteins, through disulfide bridges, and for the activity of enzymes involved in nitrogen assimilation and redox metabolism. In coffee plants, an adequate supply of sulfur contributes to the synthesis of secondary compounds, some of which act as precursors of aroma and flavor in the beverage, and favors antioxidant mechanisms associated with tolerance to abiotic stresses. S deficiency reduces the efficiency of nitrogen nutrition and compromises the synthesis of essential proteins and metabolites, resulting in lower vigor and productivity.

Deficiency symptoms

- Generalized chlorosis in young leaves, similar to nitrogen deficiency.
- Reduced growth and vegetative development.
- Decreased synthesis of secondary compounds.

Common sources of fertilization

- Ammonium sulfate (21% N and 24% S)
- Potassium sulfate (50% K₂O and 17% S)
- Agricultural gypsum (15% S)
- Elemental element (sulfur tablets)

Silicon in coffee cultivation: a beneficial element with strategic potential

Although not considered essential, silicon (Si) is classified as a beneficial element for several crops, including coffee, due to its role in tolerance to biotic and abiotic stresses. Si is deposited in cell walls in the form of amorphous silica, increasing structural rigidity, reducing water loss through transpiration, and hindering the penetration of pathogens. It also participates in induced defense processes, stimulating the synthesis of phytoalexins, phenolic compounds, and lignin. In tropical conditions, its application can result in greater photosynthetic efficiency, better nutrient use, synchronization of maturation, and greater plant resilience to stress.

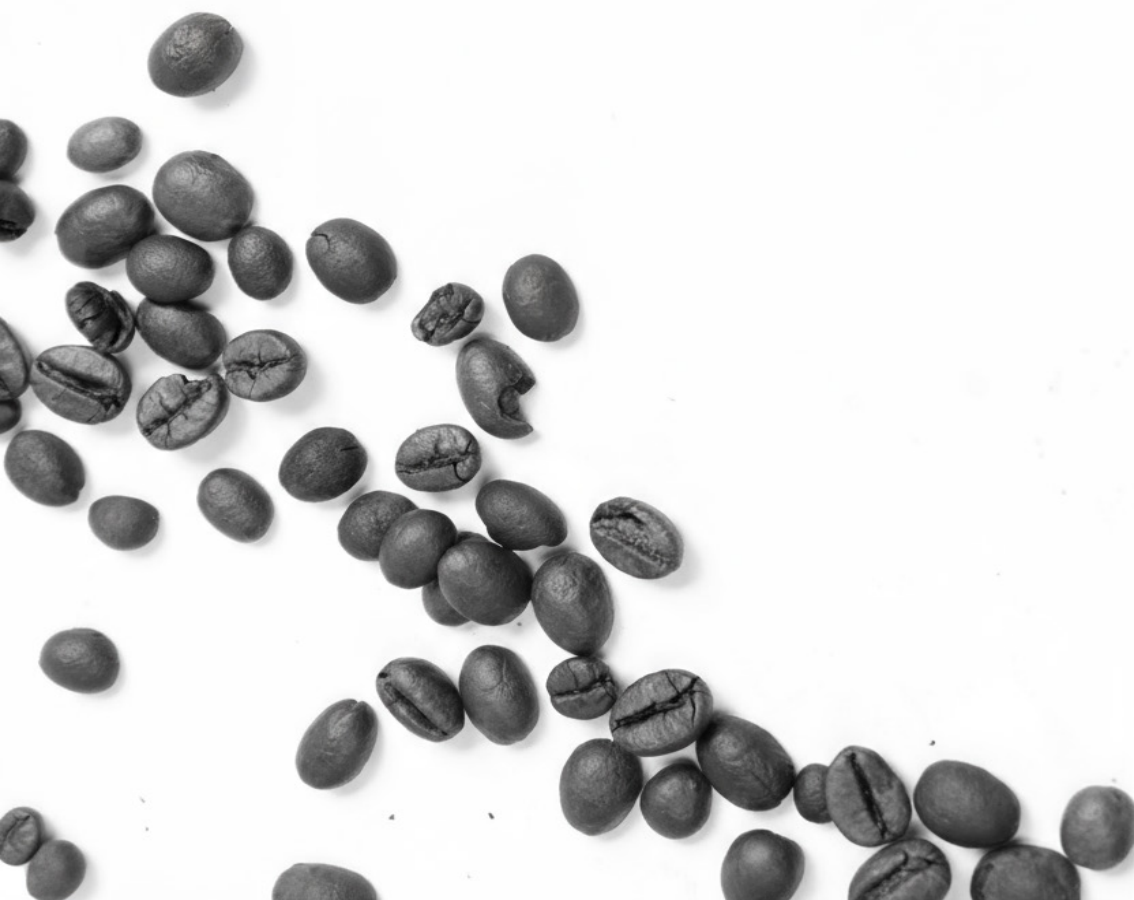
Its application is associated with:

- **Reduction of diseases:** lower incidence and severity of rust (*Hemileia vastatrix*) and cercosporiosis (*Cercospora coffeicola*).
- **Tolerance to water deficit:** greater cell rigidity, better stomatal control, and activation of antioxidant enzymes.
- **Improved quality and uniformity of ripening:** increased photosynthetic efficiency, translocation of assimilates, and synchronization of fruit development.

- **Photosynthetic stability:** preservation of chloroplasts, delayed leaf senescence, and activation of enzymes such as superoxide dismutase and catalase.

Sources used

- Potassium silicate (via foliar application)
- Steel slag (via soil application)
- Stabilized orthosilicic acid
- Fertilizers with soluble Si associated with K or Ca



MICRONUTRIENTS AND THEIR PHYSIOLOGICAL ROLE IN COFFEE GROWING

In addition to essential macroelements (N, P, K, Ca, Mg, and S), coffee plants (*Coffea arabica*) require a set of mineral micronutrients, including boron (B), chlorine (Cl), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo) and nickel (Ni), as well as beneficial elements such as cobalt (Co). Although required in extremely small quantities (mg kg⁻¹ of dry matter), these elements play a decisive role in the healthy development of plants, in the yield and sensory quality of both the green fruit and the processed bean. The absorption, internal mobility, and interactions between these nutrients directly influence the health of coffee plants, their physiological efficiency, and their resistance to diseases and biotic and abiotic stresses.

IRON (Fe)

Physiological function

In coffee (*Coffea arabica*), iron (Fe) is essential for photosynthesis and cellular respiration. It is a component of iron-sulfur (Fe-S) proteins, cytochromes, and various reductases, actively participating in the electron transport chain in both photosynthesis (photosystems I and II) and mitochondrial respiration. Fe is indispensable for the activity of nitrate reductase and nitrite reductase, in addition to acting in the regeneration of antioxidant systems, such as catalase, peroxidase, and Fe-dependent superoxide dismutase. Its adequate availability ensures energy efficiency, nitrogen assimilation, and maintenance of vegetative growth. In the soil, the Fe²⁺ (ferrous) form is more soluble and is mobilized mainly by organic acids and phenols exuded by the roots, which favors its absorption, especially in acidic soils.

Symptoms of deficiency

It is characterized by marked interveinal chlorosis in young leaves, due to the low mobility of Fe in the phloem, which can progress to almost total absence of chlorophyll. In severe cases, partial wilting of the leaflets, changes in the ultrastructure of the chloroplasts, and a reduction in the photosynthetic rate are observed, resulting in lower vegetative growth and greater susceptibility to biotic and abiotic stresses.

Phytotoxicity

Excess iron, more common in hydromorphic soils or soils with very low pH, can cause root toxicity, induce excessive production of free radicals (via the Fenton reaction), and generate antagonism in the absorption of manganese (Mn) and zinc (Zn).

Fertilization sources

Ferrous sulfate, ferrous chloride, and Fe chelates (EDTA, DTPA, EDDHA), the latter being more efficient in soils with high pH. Application can be via the soil (in cover or in pits) or via the leaves in situations of acute deficiency, respecting doses to avoid phytotoxicity.

MANGANESE (Mn)

Physiological function

Manganese (Mn) is an essential component of the oxygen evolving complex (OEC) in photosystem II, where it acts as a cofactor in the photolysis of water, promoting the release of molecular oxygen, protons, and electrons to the transport chain. It is part of the manganese-dependent superoxide dismutase (Mn-SOD) enzyme, which is crucial for the detoxification of reactive oxygen species (ROS) in chloroplasts. It acts as an activator or cofactor for more than 35 enzymes, including those involved in the biosynthesis of lignin, flavonoids, and aromatic amino acids (via shikimate), contributing to structural resistance and defense against pathogens. In addition, Mn is associated with the regulation of

cell wall formation and the functioning of the apical meristem, especially in actively growing tissues.

Deficiency symptoms

Mn deficiency in coffee plants initially manifests as interveinal chlorosis in young leaves, usually with a lighter appearance than Fe deficiency, and may progress to punctiform necrotic spots. There is a significant reduction in the photosynthetic rate, a decrease in carbohydrate accumulation, and changes in the ultrastructure of chloroplasts, which may be irreversible in severe cases.

Phytotoxicity

Excess manganese, more common in acidic and poorly drained soils, can reduce the absorption of iron (Fe) and zinc (Zn) through ionic antagonism. Leaf symptoms include brown-black spots, marginal necrosis, and, in severe cases, leaf deformities. At toxic levels, it can also negatively affect the root system.

Fertilization sources

Manganese sulfate, manganese chloride, and Mn chelates (e.g., EDTA-Mn), applied via soil (in furrows or pits) or via foliar application, according to visual diagnosis or foliar/soil analysis. In acidic soils, joint management of liming is recommended to avoid toxicity.

COPPER (Cu)

Physiological function

Copper (Cu) is an essential micronutrient that acts as a cofactor for plastocyanin, a key protein in electron transport between photosystem II and photosystem I, a critical step in photosynthesis. It participates in several oxidoreductase enzymes, including Cu/Zn superoxide dismutase (Cu/Zn-SOD), which acts in the detoxification of reactive oxygen species (ROS), protecting against oxidative stress. Cu-dependent enzymes, such

as polyphenol oxidase, catalyze the oxidation of phenolic compounds, promoting lignification and reinforcing the rigidity and integrity of the cell wall, especially in xylem and phloem tissues. Thus, Cu is involved in processes related to energy metabolism, the formation and strengthening of conductive tissues, and enzymatic defense against pathogens.

Deficiency symptoms

Cu deficiency in coffee plants manifests itself in pale leaves, often with brownish or necrotic margins, stunted growth, and shortened internodes. There may be an accumulation of unoxidized phenols, reduced lignification, and increased susceptibility to fungal and bacterial infections. In severe cases, young branches may show wilting and apical necrosis.

Phytotoxicity

Excess Cu, more common in soils with a history of intensive use of copper fungicides or with low adsorption capacity, can cause antagonism with zinc (Zn) and iron (Fe), reducing their absorption. Phytotoxicity can manifest as generalized chlorosis and reduced growth due to the blockage of other micronutrients.

Fertilization sources

Copper sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$), copper oxide (CuO), cuprous oxide (Cu_2O), copper oxychloride ($3\text{Cu}(\text{OH})_2 \cdot \text{CuCl}_2$) and copper nitrate [$\text{Cu}(\text{NO}_3)_2$], preferably applied locally and in controlled doses to avoid excessive accumulation in the soil.

ZINC (Zn)

Physiological function

In coffee (*Coffea arabica*), zinc (Zn) acts as an essential cofactor in several enzymes related to photosynthesis, plant hormone metabolism, and antioxidant balance. It is a fundamental component of carbonic anhydrase, which catalyzes the interconversion between CO_2 and bicarbonate, favoring

carbon assimilation in leaves. It participates in superoxide dismutase Zn/Cu (Cu/Zn-SOD), responsible for neutralizing superoxide radicals (O_2^-), protecting cells against oxidative damage.

Zn also stimulates the biosynthesis of auxins from tryptophan, promoting vegetative growth, internode elongation, and lateral root formation, directly impacting plant architecture. In addition, adequate levels of Zn preserve cell membrane integrity and reduce lipid peroxidation, contributing to physiological efficiency and sustained productivity.

Studies show that foliar application of Zn, especially in the form of zinc sulfate or zinc oxide nanoparticles (ZnO), increases the foliar concentration of the nutrient, raises photosynthetic rates, increases chlorophyll content, and promotes greater accumulation of leaf biomass.

Deficiency symptoms

Smaller, narrower leaves, generalized or interveinal chlorosis, shortened internodes, poor cell division and expansion, and accumulation of unmetabolized sugars in affected tissues.

Phytotoxicity

Excess Zn can retard plant development, antagonize the absorption of iron (Fe) and copper (Cu), and induce necrosis or visual symptoms similar to the deficiency of other micronutrients.

Fertilization sources

Zinc sulfate ($ZnSO_4$), zinc oxide (ZnO), zinc chloride ($ZnCl_2$), zinc nitrate [$Zn(NO_3)_2$], and synthetic chelates such as Zn-EDTA. Application can be made via soil or foliar application, and doses should be adjusted according to soil and tissue analysis to avoid toxicity.

BORON (B)

Physiological function

Although it is not directly integrated into enzymes, boron (B) is crucial in forming bridges between pectin molecules in the cell wall, stabilizing its structure and permeability. This provides stability and regulates the porosity of the cell wall. It plays an important role in the transport of carbohydrates via the phloem, in maintaining the integrity of cell membranes and in the viability and growth of the pollen tube, being indispensable for fertilization and fruit filling. In coffee (*Coffea arabica*), boron directly influences flower setting, fruit set, and fruit uniformity, impacting the final quality of the bean. This is mainly due to its participation in sugar translocation, cell division, and meristem differentiation.

Symptoms of deficiency

Flower abortion, flower and fruit drop, death of the apical meristem, fruit deformation, thick and brittle new leaves, and lower fruiting intensity. In severe cases, apical growth may stop.

Phytotoxicity

Excess boron, usually associated with foliar applications or poorly calibrated fertilization, causes necrosis of leaf margins, generalized chlorosis, and a marked reduction in productivity. As the range between deficiency and toxicity is narrow, application must be strictly controlled.

Fertilization sources

Boric acid, borax (sodium tetraborate), and ulexite (borated minerals, preferably used via the soil). Applications can be made via the soil, in low and well-distributed doses, and/or via the leaves in situations of diagnosed deficiency.

MOLYBDENUM (Mo)

Physiological function

Molybdenum (Mo) is an essential micronutrient that is part of the active center of key enzymes in nitrogen metabolism, such as nitrate reductase (NR) and nitrogenase. Nitrate reductase catalyzes the reduction of nitrate (NO_3^-) to nitrite (NO_2^-), which is then converted to ammonium (NH_4^+), a fundamental step in the synthesis of amino acids and proteins. Nitrogenase, present in nitrogen-fixing microorganisms, depends on a molybdenum-iron (FeMo-co) cofactor and is crucial for biological nitrogen fixation (BNF) in systems intercropped with legumes. In coffee, although direct BPN does not occur, Mo optimizes the use of nitrogen from both mineral fertilization and organic matter mineralization, favoring protein synthesis and photosynthesis. Its absorption occurs predominantly in the form of molybdate (MoO_4^{2-}), which is mobile in both the xylem and phloem, allowing internal redistribution and contributing to N use efficiency.

Deficiency symptoms

Diffuse chlorosis in older leaves, reduced growth and production, accumulation of nitrate in tissues due to lower nitrate reductase activity, and, in more severe cases, marginal necrosis. In seedlings, it can cause symptoms similar to nitrogen deficiency, but with high leaf NO_3^- levels.

Phytotoxicity

Molybdenum toxicity is extremely rare in agricultural systems, usually occurring only in soils with excessive application or industrial contamination. At very high levels, it can cause an imbalance in the absorption of copper (Cu) and other metals, leading to nutritional antagonisms.

Fertilization sources

Ammonium molybdate $[(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot 4\text{H}_2\text{O}]$ and sodium molybdate ($\text{Na}_2\text{MoO}_4\cdot 2\text{H}_2\text{O}$), applied via the soil. Foliar application is also effective, especially in nurseries or in situations of confirmed deficiency.

CHLORINE (Cl)

Physiological function

Chloride (Cl^-) acts as an essential cofactor in **photosystem II**, participating in the photolysis of water and helping to stabilize the **oxygen evolving complex** (OEC), a fundamental step in the release of O_2 and electrons in the photosynthetic process. It also plays an important role in **cell osmoregulation**, especially in guard cells of stomata, where it accompanies the flow of potassium (K^+) to regulate stomatal opening and closing, contributing to the control of gas exchange and transpiration.

Cl^- also influences the activity of **membrane ATPases**, such as the **V-ATPase** of the tonoplast, modulating cell turgor, water use efficiency, and tolerance to moderate stresses, such as water deficit and salinity. Although it is required in relatively larger amounts than other micronutrients (in concentrations close to secondary macronutrients), its role is specific and indispensable for plant physiology and ionic homeostasis.

Deficiency symptoms

Cl^- deficiency in coffee manifests itself through reduced stomatal opening, reduced leaf turgor, lower drought tolerance, and decreased photosynthetic efficiency. Visually, diffuse chlorosis, leaf bronzing, partial wilting, and reduced root growth may occur.

Phytotoxicity

Excess Cl^- , especially when the foliar concentration exceeds approximately **0.35–0.50% of dry matter**, can induce marginal necrosis, wilting, and symptoms similar to salt stress, including leaf dehydration and reduced growth.

Fertilization sources

Chlorine supplementation usually comes “piggybacking” with the supplementation of other nutrients. Potassium chloride (KCl), calcium

chloride (CaCl_2), magnesium chloride (MgCl_2). Application should consider the ionic balance of the system and the electrical conductivity (EC) of the soil to avoid excessive salinity and toxicity.



NUTRIENT DYNAMICS IN THE SOIL PROFILE AND THE INFLUENCE OF PHYSICAL AND CHEMICAL PROPERTIES

The efficiency with which nutrients are made available to roots is directly related to the physical-chemical dynamics of the soil, which determines the mobility and retention of essential elements. In a typical Latossolo soil found in tropical coffee-growing regions, the surface horizons concentrate most of the organic matter and mineral nutrients in available form, while the subsurface horizons constitute mineral reserves that can gradually supply the plant through deep root exploration. In this context, processes such as organic matter mineralization, adsorption to colloids, ion exchange, fixation in primary minerals (notably iron and aluminum oxides and hydroxides), and losses through leaching control the availability of nitrogen (N), phosphorus (P), potassium (K), and micronutrients.

Soil texture, defined by the relative proportion of sand, silt, and clay, plays a decisive role in nutrient availability and dynamics. In clayey Latosols, the high specific surface area and the predominance of micropores favor the adsorption of nutrients such as phosphorus (P), which binds strongly to iron (Fe) and aluminum oxides and hydroxides (Al), reducing their availability in the soil solution, even when the total content is high. In contrast, sandier soils have lower adsorption capacity but are more susceptible to losses through leaching of mobile forms, such as nitrate (NO_3^-) and potassium (K^+), especially under conditions of frequent irrigation or heavy rainfall. In addition, porosity, particularly the ratio of macropores to micropores, directly influences water infiltration and storage, profile aeration, and the ability of the root system to access deeper nutrient reserves.

Soil structure and aggregation play a central role in regulating nutrient dynamics. Stable aggregates, especially in granular form, protect organic matter from accelerated decomposition, favor the gradual release of nutrients, increase water availability to roots, and reduce susceptibility to erosion. Structural stability results not only from the presence of organic matter, but also from intense biological activity, including root growth, the action of microorganisms, and the intertwining of fungal hyphae, as well as the presence of polyvalent cations, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), which promote the formation of ionic bridges between particles. In contrast, compacted soils or soils with degraded structure have reduced total porosity and macropores, poor drainage, lower biological activity, and lower nutrient retention and cycling capacity, favoring losses through surface runoff and compromising the sustainability of the production system.

The clayey texture, associated with a high cation exchange capacity (CEC) and organic matter content, influences not only the availability of macronutrients, but also that of essential micronutrients such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B). In tropical Latossolos, the high concentration of Fe and Al oxides and hydroxides promotes strong adsorption of phosphorus (P) and micronutrients such as Fe and Mn under acidic pH conditions, reducing their solubility and availability, even when total reserves are high. Organic matter, in turn, contributes to the increase in organic CTC and forms stable complexes with Zn and Cu, increasing their availability and minimizing the risk of phytotoxicity. In coffee systems, practices such as maintaining natural mulch or intercropping with grasses have shown potential to increase the retention and mobilization of Fe and Mn in the surface layers, favoring plant nutrition during phenological stages of high demand, such as the reproductive phase.

Soil pH is one of the main regulators of nutrient availability. In tropical Latossolos, which often have a pH below 5.5, the solubility of iron (Fe), aluminum (Al), and manganese (Mn) increases significantly, which can intensify phosphorus (P) fixation by Al and Fe and, in the case of Mn, cause toxicity under severe conditions. In contrast, micronutrients such as zinc (Zn), copper (Cu), and boron (B) are less available at acidic pH, while

molybdenum (Mo), usually absorbed as molybdate (MoO_4^{2-}), also has a reduced half-life and utilization. Correcting soil acidity through liming increases the availability of P and various micronutrients, in addition to creating a more favorable environment for root development and microbial activity, optimizing nutrient cycling.

Organic matter (OM) is an essential component in nutrient retention and cycling. It provides additional sites for cation exchange, acts as a reserve for nitrogen (N), phosphorus (P), sulfur (S), and various micronutrients that are gradually released by mineralization, and improves water retention capacity and soil structural stability. In coffee systems integrated with cover crops, such as brachiaria (*Urochloa decumbens*), there is an increase in nutrient retention in the profile, increased soil enzyme activity (such as urease and phosphatase), greater incorporation of OM, and reduced N and P losses through leaching. Cation exchange capacity (CEC) is naturally high in clay soils with adequate OM content, showing a strong correlation with natural fertility and the resilience of the production system.

Cation exchange capacity (CEC), resulting from the interaction between the clay fraction and organic matter (OM), defines the amount of cations, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and ammonium (NH_4^+), that can be retained in the soil colloidal complex, reducing losses by leaching and contributing to pH stability and fertility. Soils with high CEC have greater reserves of nutrients available to plants; however, excessive application of nitrogen fertilizers, especially in ammoniacal forms, can promote soil acidification, increase the concentration of toxic aluminum (Al^{3+}) and, consequently, impair root absorption and phosphorus (P) availability.

The mineralization and cycling process mediated by microorganisms converts organic matter (OM) and plant residues into mineral forms that can be assimilated by plants: nitrate (NO_3^-) and ammonium (NH_4^+) for nitrogen (N); soluble phosphates for phosphorus (P); in addition to previously adsorbed micronutrients, which are released gradually. The intensity of this microbial activity is directly related to the OM content, moderate pH, adequate aeration, and moisture availability, attributes that depend on soil structure and porosity. In coffee systems, regenerative

practices that increase OM content have shown a positive effect on fertilizer use efficiency and mineral nutrition sustainability.

These parameters are directly related to nitrogen fertilizer management. In irrigated systems or those subjected to high doses of nitrogen fertilization, the vertical distribution of nitrate (NO_3^-) and organic matter, associated with water percolation during periods of high precipitation, makes the physical and chemical structure of the soil decisive for mitigating losses.

One of the first dimensions to be evaluated is the dynamics of nitrogen (N) in the soil profile. In coffee systems, research shows that both canopy management and the type of nitrogen fertilizer used, whether organic, inorganic, or combinations, significantly influence the vertical distribution of ammonium (NH_4^+) and nitrate (NO_3^-), in addition to affecting the microbial biomass responsible for mineralization. In agroforestry coffee systems in Indonesia, for example, pruned trees showed a 10% to 56% increase in total soil N and microbial biomass in the 0–20 cm layer, as a result of the rapid return of plant residues to the soil and the intensification of biological activity. In contrast, unpruned areas showed higher concentrations of NO_3^- and NH_4^+ at depths of 20–40 cm. These results reinforce the interaction between physical management practices, such as pruning, and soil chemical properties, such as total organic matter (TOM) content, microbial N biomass (MNB), and mineral forms of N, in nutrient retention and cycling.

In parallel, phosphorus (P) dynamics in clayey tropical Latossolos soils is strongly influenced by the intense adsorption of the nutrient to iron (Fe) and aluminum (Al) oxides and hydroxides under acidic pH conditions, which restricts its availability, even when total soil contents are high. Recent studies with controlled-release fertilizers (CRFs) and physical mixtures of MAP (monoammonium phosphate) have shown good results in the establishment phase of coffee trees, promoting gradual release of P for up to six months and resulting in consistent increases in leaf area, biomass, and P content in the soil, proportional to the applied dose. These results illustrate how the physical-chemical profile of the soil, the mineralogy of the clay fraction, and the pH play a decisive role in the efficiency of phosphate fertilization.

In addition, foliar fertilization can stimulate the synthesis of key enzymes, such as phosphatases and reductases, favoring the uptake of phosphorus (P) and nitrogen (N) directly by the leaves, regardless of their availability in the soil, which is particularly relevant in conditions of compaction or high acidity. As a management practice, it is recommended to perform foliar analyses before the flowering period in order to obtain a quick and accurate nutritional diagnosis. Based on these results, foliar application should be calibrated in terms of dose and pH of the spray (maintained between 5.0 and 6.0) to avoid phytotoxicity and ensure adequate mobility in the phloem.

Cation exchange capacity (CEC) acts as a natural buffer against variations in the availability of essential cations such as potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and ammonium (NH_4^+). Soils with higher clay and organic matter content have higher CEC, which helps stabilize pH, preserve nutrients in the colloidal complex, and reduce losses through leaching, resulting in less variation in the levels of available forms, a factor that is particularly important in conditions of high rainfall or frequent irrigation. In coffee cultivation, practices such as maintaining live cover with the planting of grasses between rows favor the accumulation of organic matter and an increase in CTC, in addition to promoting greater nutrient retention and improving the stability of soil aggregates.

The physical structure of the soil, characterized by the distribution and stability of aggregates, directly influences processes such as water infiltration and storage, aeration, erosion resistance, and solute mobility. Stable granular aggregates reduce the accelerated loss of organic matter and nutrients, contributing to a more balanced nutrient matrix. In Latossolos with recently planted coffee, practices such as the application of agricultural gypsum, the use of plant cover, and fertilization with organomineral fertilizers have shown potential to improve aggregate stability and pore space organization, favoring root growth and nutrient conservation throughout the profile.

Another fundamental aspect is soil porosity and apparent density, which determine the balance between macropores, essential for drainage and oxygenation, and micropores, responsible for retaining water available

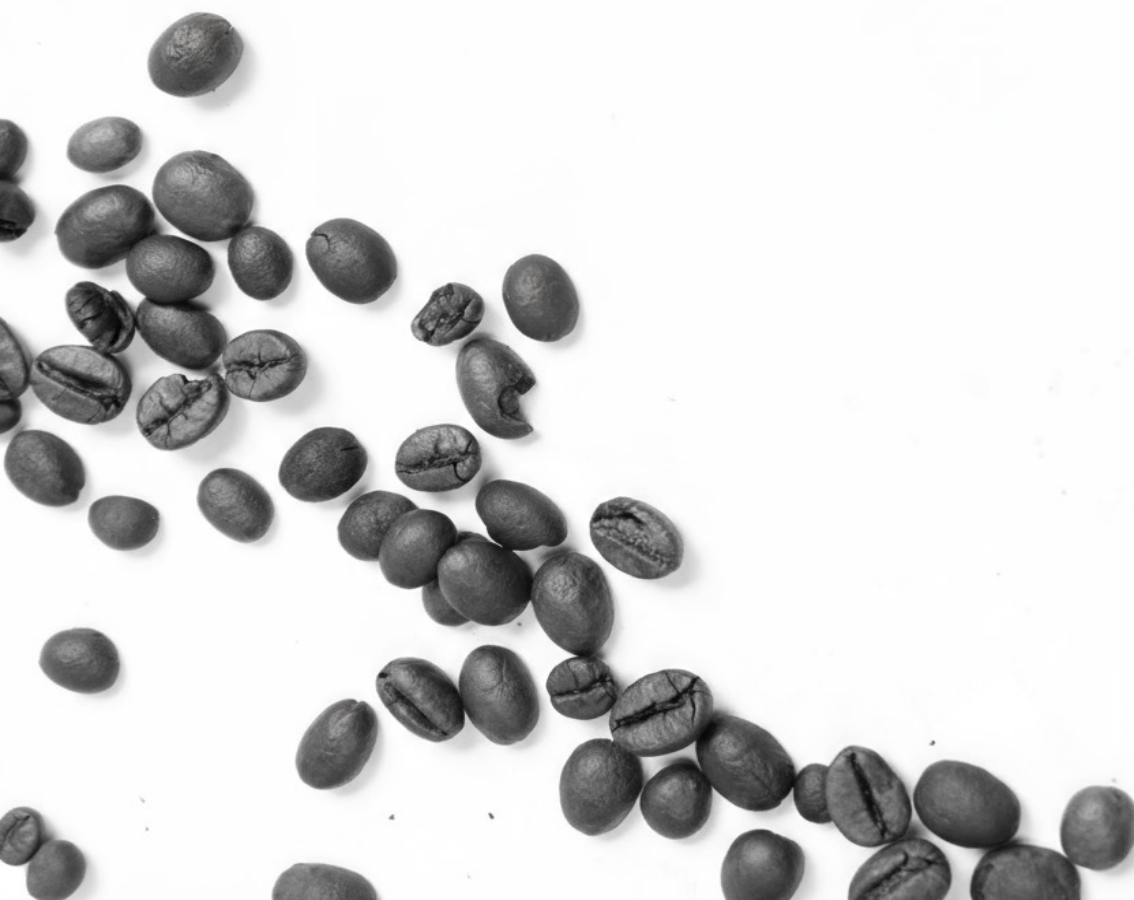
to plants. Compacted soils have high apparent density, a lower proportion of macropores and, consequently, restricted root growth, which hinders nutrient cycling and absorption. Clayey soils tend to have a higher volume of micropores, favoring water retention, while sandy soils have a higher proportion of macropores, promoting rapid drainage, but increasing the risk of leaching of mobile forms of nutrients, such as nitrate (NO_3^-) and potassium (K^+), especially when the structure is deficient.

Organic matter (OM) acts as a slow-release reservoir of nutrients, including nitrogen (N), phosphorus (P), sulfur (S), and various micronutrients. In addition, it contributes to increased cation exchange capacity (CEC) and stimulates the activity of soil microflora, as well as enzymes such as urease and phosphatase, which actively participate in biogeochemical cycles. In coffee systems that show a gradual increase in OM, either through the maintenance of vegetation cover or the use of green manure, there is greater retention of minerals in the profile, reduced losses through leaching, and increased biological activity, favoring nutrient cycling and the stability of the production system.

Soil chemical properties, such as pH, electrical conductivity (EC), and the mineralogical composition of the clay fraction, strongly influence the solubility, adsorption, and fixation of nutrients. Under acidic pH conditions, ions such as aluminum (Al^{3+}) and iron (Fe^{3+}) become predominant in the soil solution and promote phosphorus (P) fixation, reducing its availability; molybdenum (Mo), absorbed in the form of molybdate (MoO_4^{2-}), also has reduced availability under these conditions. Correcting acidity through liming raises the pH, increasing the availability of P and various micronutrients, as well as stimulating biological activity and improving conditions for root growth. High EC values may indicate a risk of salinity, affecting potassium (K) retention and ion mobility in the soil.

In summary, the interaction between the physical and chemical properties of the soil is dynamic and interdependent. Texture and aggregation influence structure, porosity, and drainage; organic matter contributes to increased CTC, improved structure, and the formation of nutrient reserves; pH regulates the solubility and adsorption of elements;

and CTC determines the cation retention capacity in the colloidal complex. This network of interactions conditions the availability of nutrients in each horizon of the profile and, consequently, the efficiency of mineral nutrition of the coffee tree.



METHODS FOR DIAGNOSING SOIL FERTILITY AND THE NUTRITIONAL STATUS OF COFFEE TREES

In coffee farming, maximizing productivity, quality, and profitability requires accurate diagnoses of both the soil and the plants. Isolated analyses of only the soil or only the leaves reduce the effectiveness of fertilization recommendations. A soil may have adequate nutrient levels, but if there are physical, chemical, or physiological restrictions that limit absorption by the roots, there is a waste of inputs and a risk of nutritional imbalances. Similarly, adequate nutrient concentrations in leaves can mask deficiencies in the soil or indicate imbalances in the relationships between elements. For this reason, integrated soil-leaf diagnosis is becoming established as an essential practice in coffee tree nutritional management.

In Arabica coffee systems in tropical Latossolos, with high acidity and low organic matter, combined analysis of soil and plant tissue allows for a more accurate interpretation of the nutritional status of the crop. This approach is complemented by established interpretation methods, sufficiency ranges, and critical levels and, when greater sensitivity to imbalances between elements in the plant is desired, by the use of DRIS in leaf analysis. This combination supports more assertive decisions on correction and fertilization throughout the production cycle.

SOIL FERTILITY DIAGNOSTIC METHODS

Sampling and laboratory

The representativeness of the analysis begins with the collection. In homogeneous plots, it is recommended to compose the sample with at least twenty subsamples per plot, collected in the layer from zero to

twenty centimeters and, periodically, also in the layer from twenty to forty centimeters to assess possible limitations in the subsurface. Sampling after harvest is common practice for planning correction and fertilization for the new cycle. In laboratories, analyses include pH, organic matter, cation exchange capacity, exchangeable bases (calcium, magnesium, and potassium), extractable phosphorus, and micronutrients such as zinc, copper, iron, manganese, and boron.

Traditional interpretation and appropriate ranges in the soil

Critical levels and sufficiency ranges are defined by regional consensus and calibration tests. For coffee trees, manuals and regional studies indicate a desirable soil pH of around 5.5 to 6.0, with base saturation adjusted according to exchange capacity at pH 7: in low-capacity soils, higher saturation targets (~80%) are necessary to achieve the appropriate pH; in medium-capacity soils, intermediate targets of 60-70%; and in soils with good capacity, targets around 60% tend to be sufficient.

For soil nutrient levels obtained with the Mehlich-1 extractor, widely used references in Brazilian coffee farming indicate the following practical guidelines: available phosphorus is adequate when above 20 mg dm⁻³; potassium is medium between 100 and 160 mg dm⁻³ and high above this range; calcium between 1.5 and 3.0 cmol load per dm⁻³ and magnesium between 0.5 and 1.0 cmol load per dm⁻³; sulfur between 5.0 and 10.0 mg dm⁻³; zinc between 1.5 and 3. mg dm⁻³. These values guide the adjustment of liming and maintenance fertilization, always considering the history and productivity goals.

DIAGNOSIS OF THE NUTRITIONAL STATUS OF COFFEE TREES

Leaf sample collection

Samples are taken from fully expanded leaves on the third or fourth pair in the middle portion of the plant during a standardized period, bearing in mind that leaf analysis can be performed at any time, provided that the reference standards for each season are followed. For crops in production, it is recommended to collect four leaves per plant from at

least twenty-five plants per homogeneous plot, totaling about one hundred leaves per composite sample. Plants with symptoms of pests, diseases, or mechanical damage should be avoided, and collection should not occur immediately after spraying.

Leaf sufficiency ranges

The levels obtained are compared with regionally established sufficiency ranges for leaves collected at the recommended time. Syntheses of classic studies for Arabica indicate the following as frequent reference ranges: nitrogen between 28.0 and 32.0 g kg⁻¹; phosphorus between 1.5 and 2.0 g kg⁻¹; potassium between 16.0 and 31.0 g kg⁻¹; calcium between 10.0 and 19.0 g kg⁻¹; magnesium between 3.5 and 5.0 g kg⁻¹; sulfur between 1.5 and 2.0 g kg⁻¹. For micronutrients, boron between fifty and eighty milligrams per kilogram; zinc between six and twenty-four milligrams per kilogram; copper between ten and twenty milligrams per kilogram; iron between eighty-one and one hundred and twenty-four milligrams per kilogram; manganese between eighty-nine and one hundred and eighty-two milligrams per kilogram.

Interpretation by critical ranges and DRIS

The critical ranges relate leaf content and productivity and are direct and operational. DRIS (Integrated Diagnosis and Recommendation System) interprets the balance between nutrients in the leaf, generating indices for each element: more negative values suggest a higher probability of relative limitation, while positive values may reflect relative excess in the balance. In coffee, DRIS has shown good ability to discriminate crops in terms of nutritional limitation and guide fine adjustments in fertilization, especially when there are imbalances between elements.

Practical advantages of DRIS on leaves

- Allows ranking of nutritional limitation, prioritizing interventions.
- Reduces the risk of excessive or insufficient fertilization by considering relationships between elements, not just absolute values.

- Complements critical ranges when the crop has multiple nutritional imbalances.

Soil-leaf correlation and integrated diagnosis

Simultaneously comparing soil and leaf results helps distinguish soil availability constraints from absorption problems. For example, adequate phosphorus in the soil but low in the leaves may indicate fixation by iron and aluminum oxides or root system limitations; high potassium in the soil with no leaf response may signal an imbalance with calcium and magnesium. Studies linking soil attributes and foliar analysis in Arabica reinforce the usefulness of this cross-referencing to interpret productivity responses.

Practical guidelines and recommended operational flow

1. After harvest: take soil samples from the 0-20 centimeter layers and, periodically, from the 20-40 centimeter layers. Request a complete analysis and interpret pH, base saturation, available phosphorus by Mehlich-1, exchangeable potassium, calcium, magnesium, and micronutrients.

2. Before flowering: collect newly mature leaves according to the indicated protocol and interpret by sufficiency intervals; when greater sensitivity to imbalances is desired, calculate DRIS indices.

3. Soil-leaf integration: cross-reference results to prioritize corrections and maintenance fertilization, distinguishing between lack of availability in the soil and absorption limitations.

4. Applications: prioritize soil fertilization for macronutrients and consider foliar supplements for critical micronutrients, such as zinc or boron, when indicated by diagnosis.

5. Monitoring: repeat soil and foliar analysis at consistent intervals throughout the cycle, maintaining a history for each plot to detect trends and adjust management for each harvest.

LIME AND GYPSUM PRACTICES IN COFFEE FARMING: EFFECTS AND RECOMMENDATIONS

Soil acidity management is a critical factor in coffee farming, especially in tropical regions with naturally acidic soils, such as the Latossolos soils widely found in Brazil. Liming and gypsum application are essential practices for maintaining high production ceilings, restoring chemical balance, and expanding root exploration.

Liming, carried out with calcitic (calcium carbonate) or dolomitic (calcium and magnesium carbonates) limestone, has as its main functions the correction of soil pH and the neutralization of toxic aluminum (Al^{3+}), in addition to providing calcium (Ca) and magnesium (Mg) as essential nutrients.

Agricultural gypsum ($CaSO_4 \cdot 2H_2O$), on the other hand, does not significantly alter soil pH, but acts to improve the root environment in subsurface layers. Its main effect is to reduce aluminum toxicity at depth, increase calcium availability, and supply sulfur (S) to the root system.

These practices influence not only plant mineral nutrition (especially Ca, Mg, S, and P), but also promote physical benefits, such as improved soil structure and porosity, and biological benefits, such as stimulation of microbial activity and particle aggregation.

This chapter will delve deeper into the mechanisms of action, effects on coffee cultivation, application recommendations, and guidelines for safe and effective management of these practices.

CALCULATION OF LIMING REQUIREMENTS AND APPLICATION RECOMMENDATIONS IN COFFEE CULTIVATION

Determining liming requirements (LR) is an essential step in chemical soil management for coffee cultivation, since the correct application of the corrective agent is crucial for neutralizing acidity, reducing aluminum toxicity, and ensuring the availability of calcium (Ca^{2+}) and magnesium (Mg^{2+}) at adequate levels. In heavily weathered tropical soils, such as Latossolos and Argissolos, acidity is often associated with high levels of exchangeable Al^{3+} and low base saturation, which limits root growth, restricts water and nutrient absorption, and compromises the productive potential of coffee trees.

The primary function of liming is to neutralize H^+ and Al^{3+} ions in the solution and in the soil's exchange complex, raising the pH to values that minimize the toxic solubility of aluminum and promote greater availability of nutrients, especially phosphorus (P) and molybdenum (Mo). At the same time, limestone provides Ca^{2+} and Mg^{2+} , elements that are essential for cell wall stability, enzyme function, and cation balance in the rhizosphere. These chemical effects are also reflected in physical improvements, such as increased soil aggregation and porosity, and biological improvements, with increased microbial activity responsible for key processes in the nutrient cycle.

The NC estimate should be based on recognized methods that not only raise the pH and base saturation but also quantitatively supply the Ca^{2+} and Mg^{2+} requirements for coffee development. Two methods are widely used:

1. Method of exchangeable aluminum neutralization and Ca^{2+} + Mg^{2+}

This method is especially suitable for soils with low cation exchange capacity (CEC), where the fixation of basic cations can compromise mineral nutrition. The formula is:

$$\text{NC (t/ha)} = Y \times \text{Al}^{3+} + [X - (\text{Ca}^{2+} + \text{Mg}^{2+})]$$

where Al^{3+} , Ca^{2+} , and Mg^{2+} correspond to exchangeable levels (cmolc/dm^3); X is the Ca^{2+} + Mg^{2+} requirement for the crop (3.5 cmolc/dm^3 for coffee); and Y is a coefficient that expresses the buffering capacity

of the soil, estimated based on texture or remaining phosphorus (P-rem), a sensitive indicator of colloid reactivity and anion adsorption capacity.

2. Base saturation method (V%)

More widespread in tropical agricultural systems, it is based on increasing the soil V% to a pre-established value for the crop, generally 60% for coffee, although values between 60% and 70% may be adopted depending on the CTC and soil texture. The formula is:

$$\text{NC (t/ha)} = \frac{T \times (V_e - V_a)}{100}$$

where **T** is the CTC at pH 7 (cmolc/dm³), **Ve** is the expected base saturation, and **Va** is the current base saturation.

After obtaining the NC, it is considered that the calculation was made for a corrective agent with PRNT = 100%, incorporated into the 0–20 cm layer. To adjust to field conditions, it is necessary to calculate the practical amount of lime (QC), according to the application conditions and product quality:

$$\text{QC (t/ha)} = \text{NC} \times \frac{\text{SC}}{100} \times \frac{\text{PF}}{20} \times \frac{100}{\text{PRNT}}$$

where SC represents the percentage of the surface effectively corrected (100% for total area, <100% for strip application), PF is the incorporation depth (cm), and **PRNT** is the Total Relative Neutralization Power of the corrective agent. In cases of application in pits (40 × 40 × 40 cm), the following is used:

$$\text{QC (g/cova)} = \text{NC (t/ha)} \times 32 \times \frac{100}{\text{PRNT}}$$

The technical recommendation is to calculate the NC using both methods, adopt the lowest value, and verify that it meets the minimum requirement for Ca²⁺ + Mg²⁺. If it does not, the value obtained by the aluminum neutralization method is used. If the final value exceeds the CTC at pH 7, this should be used as the maximum limit, preventing over-liming and associated risks, such as induced micronutrient deficiency (Zn, Mn, Fe, and B) and reduced potassium (K⁺) availability.

NUMERICAL EXAMPLE APPLIED TO COFFEE CULTIVATION

Parameters obtained by soil analysis:

- $\text{Al}^{3+} = 1.5 \text{ cmolc/dm}^3$
- $\text{Ca}^{2+} = 1.0 \text{ cmolc/dm}^3$
- $\text{Mg}^{2+} = 0.5 \text{ cmolc/dm}^3$
- $\text{T} = 6.0 \text{ cmolc/dm}^3$
- $\text{Va} = 30\%$
- $\text{X} = 3.5 \text{ cmolc/dm}^3$
- $\text{Y} = 2$ (medium texture soil)
- $\text{SC} = 100\%$ (total area)
- $\text{PF} = 20 \text{ cm}$ (standard incorporation)
- $\text{PRNT} = 80\%$

Base saturation method:

$$\text{NC}_1 = \frac{6,0 \times (60 - 30)}{100} = 1,8 \text{ t/ha}$$

Aluminum neutralization method:

$$\text{NC}_2 = 2 \times 1,5 + (3,5 - (1,0 + 0,5)) = 3,0 + 2,0 = 5,0 \text{ t/ha}$$

The lowest dose (1.8 t/ha) does not meet the minimum requirement for $\text{Ca}^{2+} + \text{Mg}^{2+}$, which is why the dose of 5.0 t/ha from the aluminum neutralization method is used. As this value is lower than the CTC (6.0 cmolc/dm^3), it is safe for application.

Practical amount of lime (QC):

$$\text{QC} = 5,0 \times \frac{100}{100} \times \frac{20}{20} \times \frac{100}{80} = 6,25 \text{ t/ha}$$

Conclusion: apply **6.25 t/ha** of lime with PRNT of 80%, incorporated uniformly in the 0–20 cm layer.

GYPSUM APPLICATION IN COFFEE CULTIVATION: THEORETICAL FOUNDATIONS AND APPLIED CALCULATION

Gypsum application consists of applying agricultural gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) to the subsurface layer of the soil (usually 20–40 cm) to provide calcium (Ca^{2+}) and sulfur (S), as well as to improve the chemical and physical environment of the rhizosphere at depth. Unlike liming, gypsum does not correct pH, but promotes the mobilization of Ca^{2+} through the profile and reduces aluminum toxicity, critical factors for root development and efficient use of water and nutrients. Due to its high solubility, gypsum acts quickly, especially in tropical weathered soils, such as the Latossolos soils of Brazil.

Criteria for Gypsum Application

Gypsum application is recommended when one or more of the following conditions are present in the 20–40 cm layer:

- Base saturation ($V\%$) less than 35%;
- Calcium (Ca^{2+}) content less than 0.5 cmolc/dm^3 ;
- Aluminum (Al^{3+}) content greater than 0.5 cmolc/dm^3 ;
- High aluminum saturation ($m\%$) — with references mentioning values $\geq 20\%$ or $\geq 30\%$ as critical limits.

Methods for Calculating Gypsum Application

1. Based on Base Saturation ($V\%$) and CTC

$$\text{NG (kg/ha)} = \frac{(V_e - V_a) \times \text{CTC}}{500}$$

Where:

- V_e : expected base saturation (%);
- V_a : current base saturation in the subsurface layer (%);
- CTC: cation exchange capacity of the same layer (cmolc/dm^3).

2. Based on the Liming Requirement (LR)

In this method, first estimate the NC for the layer of interest (e.g., 20–40 cm), and then:

$$NG \text{ (t/ha)} = 0,30 \times NC$$

Next, convert to practical quantity for application (QG):

$$QG \text{ (t/ha)} = NG \times \frac{SC}{100} \times \frac{PF}{20}$$

Where:

- SC: percentage of area to be covered (100% for total area; 75% in strips);
- PF: corrected layer thickness (in cm — usually 20 cm for a 20–40 cm layer).

3. Based on clay content

For perennial crops (such as coffee):

$$NG = 75 \times \text{Clay content (\%)}$$

This method, although simplistic, is used in the absence of detailed chemical data.

NEW METHODOLOGY FOR CALCULATING GYPSUM APPLICATION — BASED ON CALCIUM SATURATION (CAIRES & GUIMARÃES, 2018)

Recently, an innovative approach has been proposed based on empirical analysis of field experiments involving crops such as corn, soybeans, wheat, and barley, conducted on Latossolos soils under no-till farming in southern Brazil. The authors Caires and Guimarães used data mining techniques from field experiments with the application of different doses of gypsum to propose a new methodology for calculating gypsum requirements. The studies identified that the best yields were obtained when the calcium saturation in the effective CTC of the 20–40 cm layer reached approximately 60%.

Based on this finding, the authors developed a formula that calculates the gypsum requirement as a function of the difference between the desired calcium saturation (60%) and the existing saturation.

$$NG=(0,6 \times CTC_{ef}-Ca^{2+}) \times 6,4$$

Where:

- **CTC_{ef}** is the effective cation exchange capacity;
- **Ca²⁺** is the exchangeable calcium content in the 20–40 cm layer in cmolc dm⁻³;

Additional Technical Considerations

The choice of gypsum application method should be based on the availability of chemical indicators, depth of influence of the practice, and operating conditions.

The combination of approaches (V%, NC, or texture) can provide converging references, contributing to a more robust recommendation.

Excessive use of gypsum can cause leaching of magnesium (Mg²⁺) and potassium (K⁺), leading to nutritional imbalances. Therefore, the conditionality of application is crucial.



ORGANIC MATTER AND CARBON MANAGEMENT IN COFFEE FARMING SOILS

Soil organic matter (SOM) is the cornerstone of fertility and physical and biological resilience in Brazilian coffee plantations. In Latossolos and Argissolos soils typical of coffee-growing regions, SOM improves aggregation, increases water retention capacity, stabilizes temperature, and increases cation exchange capacity, effects that translate into greater nutrient use efficiency and lower vulnerability to dry spells. In practical terms, two strategic approaches increase MOS stocks and functionality in coffee farming: i) organic inputs applied to the entire area (especially agricultural compounds) and ii) cover crop management in rows and between rows; complemented by iii) the judicious use of organomineral fertilizers, which integrate organic and mineral sources to modulate nutrient availability and loss, mainly P and N. These practices should be decided based on soil and leaf analysis, productivity targets, and management history, always adjusted to the variability of the terrain.

When managing organic compounds applied to the entire area, priority is given to stable material (mature compost) with an intermediate C:N ratio, low impurity content, and good sanitation. In mature coffee plantations, surface distribution after harvest takes advantage of the subsequent rainy season for gradual incorporation, feeding the microbial biomass and reducing out-of-phase mineralization peaks. In areas susceptible to erosion, application should follow the contour lines, and the rate should be adjusted to the carbon input target ($\text{kg C ha}^{-1} \text{ year}^{-1}$) and the need for base correction, avoiding overlap with liming and gypsum application. Where available, compounds derived from residues from the system itself (coffee mulch, pruning residues, composted bark/pulps) close cycles, increase labile SOM, and feed more stable fractions in the medium

term. In operational terms, maintaining continuous surface cover over the canopy projection strip (under the skirt) improves the distribution of active fine roots and reduces soil splashing on the fruits.

Cover crops in rows and between rows, especially brachiaria, play a central role in building SOM and physical structure. Periodic cutting with biomass directed toward the coffee row acts as a carbon and nutrient “carpet,” favoring the formation of biopores, more stable aggregates, and water infiltration. Trials in Minas Gerais show that brachiaria intercropping between rows, managed by cutting and with the material thrown onto the row, reduces susceptibility to disintegration and improves pore distribution; when this cover is combined with surface gypsum application, there is greater root exploration at depth and better access to water in the profile, a critical effect in dry years. Fine tuning consists of choosing species and densities that do not compete excessively for water in winter and synchronizing cuts with the phenology of the coffee tree to maximize the coincidence between N release and demand phases.

The synchronization of nitrogen (N) with the phenology of the coffee tree is decisive in transforming MOS and fertilization into productivity. In rainfed areas, a practical and robust scheme for mature crops, calibrated by soil and leaf analysis and production targets, is to fractionate N into 3 to 5 applications aligned with physiological phases: (1) post-harvest/early rains, prioritizing reserve replenishment and sprouting; (2) post-flowering, to support setting; (3) fruit expansion (spring-summer), the phase of greatest drainage; and, when necessary, (4) supplement during filling, observing the risk of “washing” under heavy rains. In irrigated areas, the fractioning can be even finer via fertigation. In all cases, living cover and organic mulch reduce volatilization and leaching, improve soil-plant synchrony, and often allow for a reduction in the total dose without loss of performance. The N:K balance in the cover, adjusted to the expected yield, is particularly important to avoid physiological disorders and leaf fall.

Phosphorus (P) deserves special attention in the highly weathered soils of Brazilian coffee farming. The strong interaction between P and Fe/Al oxides and surface stratification under conservation management require a combined strategy: P correction with soluble sources located in the active root zone; maintenance of SOM and cover to increase organic

complexation and reduce fixation; and use of organomineral fertilizers when available, as the organic matrix acts as a “buffer” that gradually releases P, creates microzones of higher microbial activity, and can stabilize availability in the 0–10 cm layer.

In no-till or minimum tillage systems, it is common to observe a surface P gradient; therefore, sampling should stratify layers (0–5; 5–10; 10–20 cm) in the row and between rows so as not to overestimate or underestimate the nutrient. In practice, when planting new areas, the combination of “phosphorus in the furrow/strip + organic matter + surface protection” tends to be more efficient than broadcast applications alone.

The synergy between agricultural gypsum and living cover deserves a place in medium-term planning. Gypsum, by providing Ca and S and promoting the movement of Ca^{2+} at depth, improves the chemical environment of the subsoil and, associated with the constant supply of roots and residues from cover crops, promotes stable aggregation, more macropores in layers below 20–40 cm, and a deeper and more distributed root system. Field trials on Latossolos soils have shown precisely this effect: high doses of gypsum applied to the surface, combined with the management of brachiaria between rows, increased aggregate stability and root exploration, connecting the chemical benefit (Ca/S at depth, lower Al^{3+} activity) with the physical benefit (biopores and functional porosity). In practical terms, gypsum application should follow technical recommendations (profile, clay content, V% and Ca/S requirement) and be accompanied by active cover; without biomass and roots, part of the structural gain is lost.

Spatial variability within the plot is the rule, not the exception, in coffee plantations with undulating relief and soils with varying clay content and slope position. Incorporating precision agriculture principles improves the return on MOS and fertilization practices. An efficient protocol is: (i) use relief/apparent conductivity and production or vigor maps to define 2–4 management zones; (ii) sample soil by zone and position (row vs. inter-row) in shallow and subsurface layers; (iii) adjust doses and forms, e.g., more organic matter and K on tops and shallow shoulders, focus on P located in strips with higher clay and higher fixation, and stagger gypsum

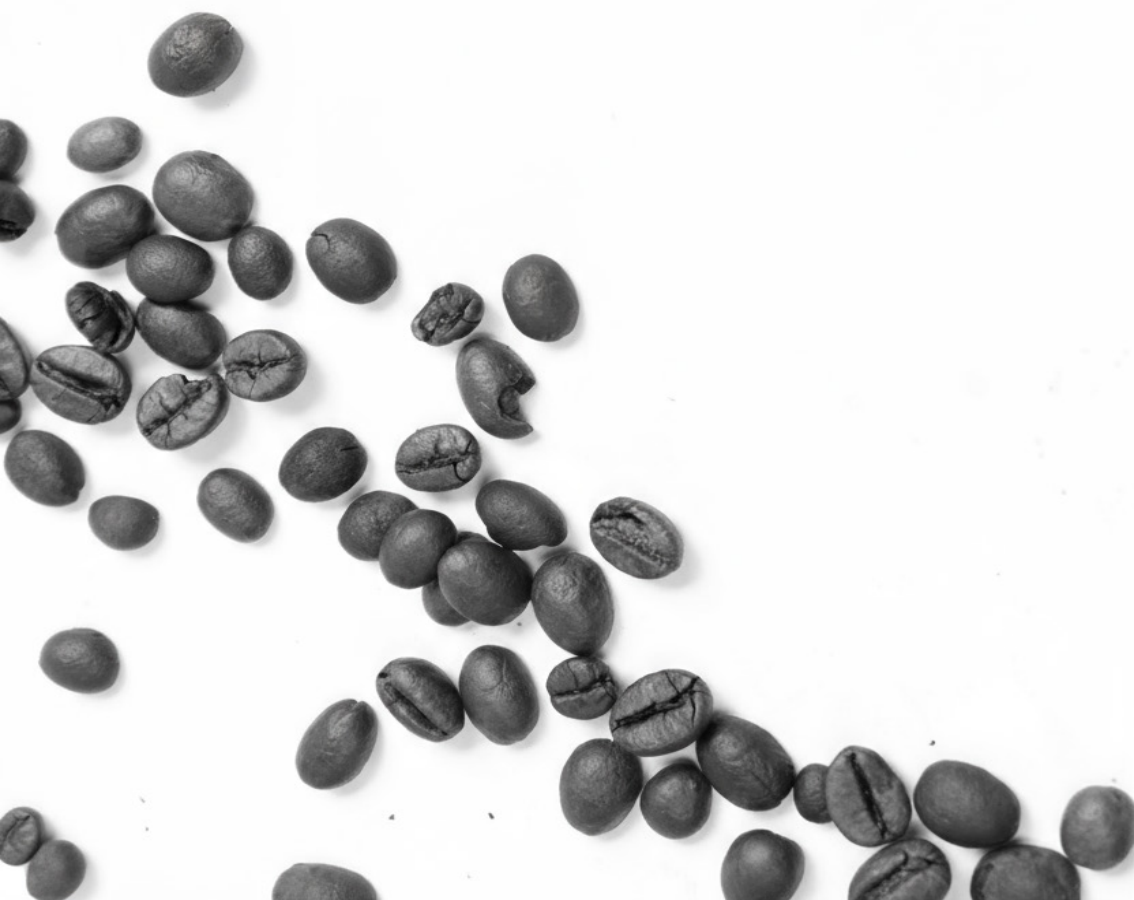
where the subsoil is more limiting; (iv) when available, operate variable rate equipment for NPK and amendments. In crops with canopy distribution control, the location of fertilizer “under the skirt” improves efficiency by coinciding with the highest density of active fine roots, reducing losses.

Organomineral fertilizers are gaining ground as a tool for aligning C input, gradual nutrient release, and operational efficiency. In Arabica coffee, field results indicate that organomineral fertilizers formulated to meet the same P_2O_5 dose as the mineral recommendation can maintain or exceed productivity, with additional benefits in soil P and K availability when applications are split. In terms of management, organomineral fertilizers work particularly well when combined with living cover crops and organic mulch in the row, as the organic matrix of the product, combined with the addition of residues, reduces salinity pulses and improves supply-demand synchronization. The practical recommendation is: use organomineral as part (or all) of maintenance fertilization, keep the split application aligned with phenology, and check the cost per unit of nutrient delivered, in addition to the logistics of band application.

Quantifying and monitoring gains is part of success. For MOS and soil organic carbon (SOC), periodic sampling is recommended in layers 0–10, 10–20, and 20–40 cm in the row and between rows; whenever possible, include particulate carbon and biological indicators (microbial biomass, enzymatic activity). For P, stratifying the surface layers (0–5 and 5–10 cm) helps interpret the effect of conservation management. Physical indicators (aggregate stability, soil density, and infiltration) reveal structural responses to cover and gypsum practices. At the operational level, record cover cuts, dates, and doses of compost/organomineral/gypsum and link them to production maps: this allows for quick adjustment of management zones and verification of results.

From a regenerative coffee farming perspective, SOM management and the practices mentioned above are at the heart of the system. The logic is clear: permanent living cover crops and botanical diversity maintain carbon flow to the soil; organic compounds close cycles and increase stable stocks; organomineral compounds modulate the availability of nutrients, especially N and K, without peaks of loss; and gypsum application, when indicated, “opens” the subsoil to roots and water, reducing dependence

on inputs and climate risk. On Brazilian farms that align these fronts, vigorous cover between rows, targeted cutting, farm-produced compost, fractionated and localized fertilization (including organomineral) “under the skirt,” gypsum according to profile diagnosis and zone-based decisions, more stable crops are observed in difficult harvests, better fertilizer use efficiency, and tangible advances in soil health indicators. In short: regenerating coffee means managing the carbon cycle in the soil with science, consistency, and good agronomy.



MINERAL NUTRITION AND ITS EFFECTS ON COFFEE QUALITY

The mineral nutrition of coffee trees has a decisive influence on the physical, chemical, and sensory quality of the beans, because it governs the formation, accumulation, and preservation of precursors of aroma, acidity, and sweetness (sugars, chlorogenic acids, volatile compounds, and phenols), in addition to affecting the integrity of membranes during processing and roasting. Accumulated evidence shows that quality is rarely explained by a single nutrient: it emerges from the balance between elements, the chemical state of the soil (acidity, loads, base saturation) and the fine tuning of sources and divisions throughout the cycle. In practical terms, crops that combine adequate supply with balanced proportions of macronutrients and good organic matter build-up tend to produce more uniform beans and cleaner, sweeter, and more consistent cups.

Nitrogen remains central for its role in photosynthesis, protein synthesis, and vegetative growth, but management should avoid both deficiency and excess. High and poorly timed doses push the plant into vegetative growth, dilute sugars, and can penalize the body and sweetness of the coffee; on the other hand, adequate and well-spaced levels (especially under fertigation) favor photosynthetic rate, formation of aromatic precursors, and more uniform maturation. At the N–K interface, fertilization studies in coffee show that balanced proportions between these two nutrients are associated with better sensory scores and a more favorable chemical composition of the bean; both N and K imbalances can increase electrical conductivity and potassium leaching from the beans, signs of membrane fragility that are often correlated with quality loss.

Potassium, in turn, is crucial for sugar translocation, turgidity, and fruit filling. Its deficiency reduces the percentage of high sieve pass

and increases physical defects. However, excess K causes antagonism with magnesium and calcium, with repercussions on quality. Balancing K:Mg is especially relevant in tropical soils where management favors increasing exchangeable K. In addition to the dose, the source of K can introduce sensory nuances: trials with KCl, K₂SO₄, and KNO₃ show that all sources can sustain productivity and, in many scenarios, high-scoring coffees; under some conditions, however, potassium sulfate is associated with greater sweetness and less bitterness, while potassium chloride, when dominant and poorly managed, can favor less desirable attributes. There is no universal “winning source.” KCl often offers the best cost-benefit ratio, but when the goal is to maximize fine sensory attributes, reducing chloride input, combining sources, and using fractionation tends to be a prudent choice. The very presence of Cl⁻ in the system requires attention: accumulations can interfere with enzymes linked to browning and membrane stability; adjusting sulfur and using K₂SO₄ in part of the program often mitigates these effects.

Calcium and magnesium support cell walls and membranes, signaling, and, in the case of Mg, chlorophyll itself. Good Ca and Mg saturation inhibits Al³⁺ toxicity, improves soil structure, and promotes water retention/supply, creating a physical-chemical environment that preserves grain development and tissue integrity during drying.

In many Brazilian coffee-growing regions, correct liming (guided by soil analysis and realistic base saturation targets) is an essential step for overall quality, because it raises Ca and Mg, moderates acidity, and also reduces P fixation. It is precisely in phosphorus that total organic carbon (TOC) plays a strategic role.

In highly weathered Latossolos and Argissolos soils, rich in Fe and Al oxides, applied P tends to be rapidly adsorbed, becoming less available to roots. The increase in TOC acts on three fronts: (i) humic substances and organic acids compete with phosphate for adsorption sites and complex Al and Fe, blocking active fixation points; (ii) environments with higher TOC generally exhibit higher residual phosphorus (P-rem), a well-established indicator of lower soil propensity to retain P; and (iii) higher microbial activity increases the action of phosphatases and the mineralization of organic P. In practice, this translates into better efficiency in the use of

applied P and, therefore, a higher probability that the coffee tree will maintain reserves of aroma precursors and balanced acidity. Strategies such as adding residues (including coffee husks and compost), using organomineral fertilizers, cover crops, and conservation management increase TOC while building physical stability, which contributes to more uniform maturation and crop consistency.

Phosphate fertilizer management in tropical soils, therefore, should integrate three pillars: acidity correction (liming), organic matter (TOC) building, and source positioning/splitting. Localized application in strips, the use of sources with solubility compatible with soil reactivity, and fractionation in irrigated or higher vegetative growth systems reduce losses and improve soil-plant synchrony. The evaluation of P-rem in plot monitoring is a practical tool for adjusting both the dose and the source strategy, since it informs how strongly that soil tends to retain P.

Among micronutrients, boron, zinc, manganese, iron, and copper stand out. Boron, which is commonly lacking in sandy tropical soils or soils with low organic matter content, is linked to flowering, setting, and uniformity of fruiting; its deficiency leads to malformation and shattering, with direct effects on screening and, indirectly, on quality. Zinc and manganese participate in key enzymatic pathways and the antioxidant system; zinc, for example, is related to the synthesis of auxins that modulate fruit growth and filling, while copper plays a structural role in oxidase enzymes and health, with indirect impacts on the preservation of aromatic precursors. The critical point is to maintain adequate ranges with minimal antagonism and without exceeding toxicity levels, which reinforces the need for periodic leaf diagnosis to adjust micronutrients with precision.

The edaphic background and canopy management also modulate sensory expression. Soils with better structure, greater porosity, and higher residue input stabilize moisture and temperature, cushion stress, and tend to sustain more predictable sensory profiles. Systems with well-designed shade, suitable species, and compatible density and architecture can increase residue input, increase TOC, and moderate temperature extremes without necessarily reducing quality; however, the response depends on the environment and genetic material, and the ultimate goal (quality, productivity, mechanizable harvest) should guide the decision. In crops

with high insolation and low residue input, caring for pH, organic matter, and K–Mg–Ca balance is particularly relevant so as not to penalize cup attributes.

As an integrated practical guideline, nutritional programs aimed at fine coffees should: (1) begin with a plot diagnosis, combining soil (with P-rem when appropriate) and leaf analysis; (2) pursue a balance between N and K, avoiding extremes that increase K leaching from the beans and electrical conductivity; (3) manage K with attention to antagonism with Mg and the presence of Cl^- , choosing sources and combinations consistent with the sensory target and cost; (4) build COT continuously (residues, cover, organomineral, conservation management), as this is one of the most consistent levers for increasing P availability in tropical soils; and (5) maintain acidity in a moderate range with judicious liming to raise Ca and Mg and reduce phosphate fixation and Al^{3+} toxicity. When all these pieces fit together, the result is a more efficient nutrient use system, with physically superior beans and a sweeter, cleaner, and more stable sensory profile over the years, which is exactly what the specialty coffee market tends to reward.

TECHNICAL AND PRACTICAL FERTILIZATION RECOMMENDATIONS FOR COFFEE TREES

1) General principles underlying the recommendation

Consistent fertilization of coffee over many years requires alignment of three pillars: diagnosis (soil and leaves), production expectations, and application efficiency and nutrient source. In the diagnosis, soil analysis guides what to correct and replace; leaf analysis indicates how the plant responded to management and where to adjust the fine (especially nitrogen, potassium, and low-mobility micronutrients, such as boron and zinc). As coffee trees alternate between years of higher and lower yields, it is recommended to estimate productivity with caution; when the expected harvest is well below the previous “high” harvest, work with the average between the two so as not to reinforce bienniality. This care, combined with balanced and split fertilization, is a central part of management that cushions harvest fluctuations.

In the field, efficiency comes from the “4Cs”: the right fertilizer, right dose, right place, and right time. In rainfed coffee, dividing N and K into 3–4 applications throughout the rainy season reduces losses due to volatilization and leaching. Placing the fertilizer under the skirt (on both sides of the plant, preferably) puts the nutrient in the zone of highest active root density, increasing the response per unit applied. In irrigated systems, fertigation dilutes the doses into more frequent applications, with similar practical effects: more utilization, less loss.

2) Liming and gypsum application

Liming is the chemical basis of the coffee tree’s root environment. It increases base saturation, neutralizes toxic Al^{3+} , supplies Ca and Mg, and increases effective CTC; as a result, it improves P availability and

N and K efficiency. In coffee systems, deep liming (incorporated in the preparation before planting) favors root exploration in the subsurface, reducing dependence on the moist surface layer only during the first rains. In established crops, smaller, recurring annual doses concentrated in the root domain maintain pH in a favorable range and replenish Ca/Mg removed by harvesting and leaching.

Agricultural gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) does not correct pH, but provides Ca and S and carries Ca^{2+} to deeper layers, improving the structure and chemistry of the subsurface (base saturation and Ca:Al ratio) and creating a root “corridor” for water and nutrients. In soils with subsurface acidity and low Ca content at depth, gypsum is valuable as a supplement to liming. During implementation, S can also be supplied by simple superphosphate and, later, by ammonium sulfate when part of the N is supplied in this form.

Practical guideline: liming determined by soil analysis and applied before phosphate fertilization; gypsum used as a profile tool when indicated by subsurface chemistry. The specific chapter on liming/gypsum application in the book covers the calculations; here we reinforce why these corrections make fertilization more efficient throughout the cycle.

3) Planting fertilization

Agronomic objective: establish a chemically favorable and deep environment for new roots, providing localized phosphorus (short diffusion), supplying potassium in poor soils, adding S, and initiating biological dynamics with organic matter.

How to compose pit/furrow fertilization

Well-cured organic matter/compost: mixed with the soil in the pit improves structure, increases CTC, complexes Al, and contributes micronutrients. As a reference for pit assembly: a typical pit measuring $0.25 \times 0.20 \times 0.30$ m contains $\sim 15 \text{ dm}^3$ of soil; in a soil:OM ratio of 4:1, it can hold about 3 L of OM mixed with 12 L of soil. This does not replace mineral fertilization, but complements it and makes it more efficient.

Phosphorus (P_2O_5): due to its low mobility, it should be applied at planting and at depth, incorporated and homogenized into the soil of the hole/furrow. The dose depends on the P content in the soil (using your laboratory method) and the texture: clay soils require more P to overcome fixation, sandy soils require less. Usual sources: simple superphosphate (provides Ca and S), MAP, or formulated mixtures; choose based on availability and the S/Ca balance in the system.

Potassium (K_2O): application in the hole/furrow is mandatory when analysis indicates low availability. Although seedlings require little K, anticipating part of the application at depth favors initial reserves and vegetative growth. In clay soils, use the calculated dose to achieve the target content in the hole; in sandy soils, reduce the dose proportionally to avoid salinization. Sources: KCl, K_2SO_4 (the latter adds S and is useful when there is chloride restriction).

Sulfur (S): enters through the SSP in the hole/furrow and continues to come with ammonium sulfate in coverings during the first two years. Alternatively, agricultural gypsum at planting supplies S and Ca gradually.

Micronutrients: OM usually meets the initial needs; if the history/soil is poor, consider B and Zn already in the initial phase, with caution to avoid excess (the windows between sufficiency and toxicity are narrow). When necessary, correct B in the soil and Zn via foliar application later on.

Operational: mix the fertilizer thoroughly into the soil, avoiding the formation of concentrated pockets and direct contact between granules and roots. When planting in furrows, calculate the doses per dm^3 of soil effectively incorporated (the lower half of the furrow, where the soil and fertilizers are actually mixed) and distribute along the row before closing.

4) Formation fertilization

Agronomic objective: to build a canopy and root system with continuous growth, without stimulating vegetative imbalances, and to prepare the plant to enter production with adequate architecture and reserves.

How to determine doses

N (start and vigor): in the 1st and 2nd years, the dose is based on a table that considers the planting system (conventional × dense) and, in

the 2nd year, the eventual demand of the fruits is added if there is early production. In general, as spacing becomes denser, the dose per plant decreases and the dose per area increases (more plants per hectare making better use of the fertilizer). A fraction of the N can come as ammonium sulfate to ensure S in the system.

P and K (root architecture and osmotic balance): calculated according to nutrient content in the soil and age/system. P remains critical for root formation and should continue to be localized; K advances as the canopy expands and the first fruits approach.

When and where to apply

In rainfed areas, divide into portions during the rainy season: for example, 3 applications (beginning, middle, and end of the rainy season). Place the fertilizer under the skirt of the coffee tree, on both sides of the plant, increasing contact with the absorbent roots.

In irrigated areas, fertilize more frequently with N and K, keeping P mainly in soil application (or fertirrigated with compatible sources), always avoiding high concentrations in the bulb to prevent salinization.

How to express per plant and per hectare?

During formation, many recommendations are given per plant (g/plant) and vary with density. To plan logistics, convert to kg/ha by multiplying by the effective population. Conversion example (merely illustrative of the calculation): if technical guidance for your spacing indicates 120 g of N per plant and you have 5,000 plants/ha, this corresponds to 600 kg of N/ha per year; dividing into 3 parcels, each pass takes 200 kg of N/ha (adjust finely according to leaf analysis and plot response).

5) Production fertilization

Agronomic objective: sustain annual exports through fruit and maintain structure (branches and leaves), modulating doses so as not to amplify bienniality.

How to determine doses

Work with the expected crop yield, soil conditions (P and K), and, when available, other factors.

A real example of combining these variables, for a scenario with low P and K and a relevant harvest expectation, leads to a level of around N 450 kg/ha/year, P_2O_5 80 kg/ha/year, and K_2O 450 kg/ha/year. This N: P_2O_5 : K_2O ratio of $\approx 5.6:1:5.6$ is useful for guiding the choice of commercial formulas or simple mixtures that achieve the target with a minimum number of passes.

Per plant x per hectare (field example). The tables used for coffee also allow you to read the requirement per plant in g/plant when working with “liters of cherry per plant” and the range of plants/ha. To illustrate the reasoning: a common combination in a coffee plantation with a lower population may determine something like ~ 150 g of N, ~ 28 g of P_2O_5 , and ~ 150 g of K_2O per plant in a year of higher demand. At 4,000 plants/ha, this would mean, per hectare, about 600 kg N, 112 kg P_2O_5 , and 600 kg K_2O . Note that the “per plant” reading changes with density and pending productivity; therefore, when planning purchases, always convert to kg/ha for your field, validating with soil/leaf.

Installments and timing

In rainfed crops, 3 to 4 applications: one after flowering (to replenish reserves), one during the expansion phase (fixation), one during grain filling and, when appropriate, one after harvest to promote regrowth and recovery.

In irrigated fields, divide N and K into weekly or biweekly applications in the irrigation water during the active period. P can be added as phosphoric acid/phosphate compatible or in strategically positioned solid applications.

Location and losses

Depositing the fertilizer under the skirt, reaching both sides of the plant, is operationally simple and increases the efficiency of N and K.

For N, losses due to volatilization (urea) and leaching (mainly in sandy soils) require smaller rates and application to moist soil or when rain is expected. Alternating sources (urea, ammonium sulfate/nitrate) helps manage losses and, in the case of sulfate, adds S.

Regarding S, when there is no soil analysis for S, regional practices work as a rule of thumb between $\sim 1/8$ of the N dose as S in low S scenarios, reducing to $\sim 1/16$ when soil S is in the medium range; many commercial formulas already deliver part of this S.

Strategic micronutrients in production

Boron (B): essential for flower setting, it has low mobility in the plant; therefore, the focus is on the soil. In B-poor soils/trails, the strategy is to split the application to the soil into 2–3 passes along the water (typical annual dose in the order of 2–3 kg B/ha, adjusted by analysis).

In situations of acute deficiency, emergency foliar application with boric acid at $\sim 0.5\%$ (5 g/L) is used, without foregoing soil application to sustain the next cycle.

Zinc (Zn): responds well to foliar spraying during peak vegetative growth (spring–summer), with zinc sulfate heptahydrate at $\sim 0.5\%$ (5 g/L) or equivalent chelates; 2 applications during the period normally correct the situation.

Manganese and copper are added according to analysis and phytosanitary history; copper often comes from fungicides and is already part of the balance.

Quantities linked to nutrient export

Each 60 kg bag of processed coffee removes mainly N and K from the system; average values in the literature use, per bag, approximately ~ 6.2 kg of N, ~ 0.6 kg of P_2O_5 , and ~ 5.9 kg of K_2O . This “replacement per bag” approach complements the soil/leaf analysis method and helps to check whether the plan is underfeeding high-yield crops.

6) Management to reduce bienniality (linking theory and practice)

Bienniality increases when the crop “empties” in a high year and does not replenish reserves for the following year. Three decisions reduce this effect:

- Estimate the dose using the average between the high (previous) harvest and the expected harvest when the next one is well below — this cushions the drop;
- Split N and K to match supply and demand and reduce losses;
- Do not neglect post-harvest (input to replenish leaves and branches that will sustain the next crop). Added to this is the maintenance of Ca and Mg via liming, S in the system, and timely correction of B and Zn to favor flowering and fixation.

7) Good operating practices (essential)

Sampling: soil from a homogeneous plot, usual depths (surface and subsurface of interest to the root system) and history of the area; leaf collection before flowering, following your laboratory protocol (pair of leaves, part of the branch, and number of plants sampled).

Source compatibility: no “homemade” mixtures without checking compatibility (e.g., urea with phosphoric acid requires careful handling; mixtures with boron/zinc in tanks require prior testing).

Climate and humidity: under solid cover, avoid applying before dry, hot days; prefer moist soil and a forecast of moderate rain.

Distribution: bands under the skirt, on both sides. In granules, applying on top of the skirt allows the product to “descend” between the leaves to the soil without burning the foliage.

Documentation: record date, product, dose (per plant and per hectare), soil moisture, and observations; cross-reference with analyses to improve decision-making in the next cycle.

8) Summary applied by plant life stage.

Planting — Mix into the soil of the planting hole at depth (source according to strategy: SSP, MAP, etc.) according to the soil’s P content and

texture; supply K in the planting hole when the soil indicates a deficiency, respecting the soil type (less in sandy soils to avoid salinization); ensure S via SSP/gypsum and complete Ca/Mg via prior liming. Add well-cured MO (reference: about 3 L in a standard 15 dm³ hole) to improve the physical and chemical properties of the seedbed. In areas with a history of low B and Zn, consider a cautious start with these micronutrients, prioritizing B in the soil and Zn later via foliar application.

Formation (1st–2nd years) — Structure N based on the planting system (lower g/plant in dense areas, but higher kg/ha), using part as ammonium sulfate to carry S along; adjust P and K according to soil levels. In rainfed areas, divide into 3 passes throughout the rainy season; in irrigated areas, apply frequent fertigation with N and K, preferably keeping P in localized soil applications. Always position under the skirt, on both sides. If there is early fruiting in the 2nd year, add the fruit demand to the annual calculation.

Production — Define the quantities by combining expected productivity, P and K levels in the soil and leaves to adjust N. As a practical reference for demanding scenarios, work with around N ~450 kg/ha/year, P₂O₅ ~80 kg/ha/year, and K₂O ~450 kg/ha/year, modulating according to the field and targets. A “per plant” reading of ~150 g of N + ~28 g of P₂O₅ + ~150 g of K₂O may occur in less dense crops with high potential; always convert to kg/ha according to your population. In rainfed crops, 3–4 plots (pre-flowering to grain filling, with post-harvest reinforcement when appropriate); in irrigated crops, fortnightly/weekly via fertigation. B should enter the soil (foliar supplement only if there is an acute deficit); Zn responds well to 0.5% zinc sulfate in 2 sprays during the season of greatest growth. For S, ensure the proportionate fraction to N (rule of thumb for the system when the soil does not indicate S), remembering that NPK and ammonium sulfate formulations already contribute. And always locate under the skirt on both sides to take advantage of active roots and reduce losses.

FUTURE CHALLENGES AND INNOVATIONS IN FERTILITY AND NUTRITION IN COFFEE FARMING

Brazilian coffee farming is going through a time when resilience has become synonymous with competitiveness. More extreme weather, heterogeneous soils, prices, and availability of fertilizers subject to exchange rates: all of this puts pressure on management and calls for technical choices that preserve margins without sacrificing health, vigor, and quality. In this context, soil fertility and nutrition are no longer just a question of “what and how much to apply,” but rather how, when, and where to apply, based on diagnosis, simple execution, and continuous verification of results.

The first challenge is to deal with soil and crop variability. In many coffee-growing regions, differences in relief, texture, management history, and erosion cause plots to respond unevenly to inputs. Innovation here does not need to be complicated: stratified sampling by management zones, simple maps of pH, V%, P, and K, and recommendations tailored to the reality of each zone can transform a nutritional program. This is precision agriculture in its most accessible form. When possible, variable rate application of lime, gypsum, and P/K reduces waste and increases uniformity.

Drones and satellite imagery help identify canopy unevenness and prioritize areas, but the heart of the process remains repeatability: sampling the same zones, at the same times, comparing trends across harvests. With this discipline, the farm learns from its own data and stops “fertilizing by the average.”

The second axis is the fine marriage between nutrition and climate. Shorter rain windows, mid-season dry spells, and heat waves increase

losses through volatilization and leaching and, consequently, reduce fertilizer efficiency. The answer starts with planning: schedule fertilization to coincide with rain or irrigation, avoid surface applications on very hot and dry days, and when incorporation is not feasible, prioritize urea with a urease inhibitor. Phosphorus yields more when applied locally, limiting contact with the soil; potassium, in sandy environments or at risk of concentrated rain, responds well to smaller and more frequent applications. In irrigated areas, fertigation allows supply and demand to be synchronized with precision, provided that salinity, application uniformity, and soil/plant water status are monitored. The practical message is simple: the same nutrient can have very different efficacies depending on the form and timing.

In nutrient use efficiency, so-called “efficiency-enhancing technologies” offer real gains when well positioned. Urea with urease inhibitor reduces losses due to volatilization when surface application is unavoidable; in specific scenarios (tight logistics, sandy texture, regular irrigation), controlled-release sources help simplify schedules and reduce peaks and valleys in availability. Nitrification inhibitors can be part of the strategy, respecting the soil, climate, and application system. None of this replaces the basics: proper liming and, when necessary, gypsum application to improve the root environment at depth. It is common to see attempts to “sophisticate” sources without adequate pH correction; in this case, you pay more for a benefit that the soil cannot deliver.

Treating soil as biological capital is the third leg of resilience. Organic matter, aggregate stability, porosity, and microbiota determine how well crops utilize fertilizer and withstand stress. Organomineral fertilizers from good sources, stabilized compost and manure, combined with green manure and straw management, build an environment that retains water, cycles nutrients, and protects against extremes. Bio-inputs can add value, provided they are used for a clear purpose: phosphorus solubilizers in soils with high fixation power, growth promoters to stimulate roots in critical phases, mycorrhizae in conditions where symbiosis is technically indicated. The key point is traceability and evaluation: registered product, defined dose and timing, marked plot, and comparison with a mirror area. Without this record, there is no way to separate luck from results.

There is also a risk management component that cannot be solved with agronomy alone. Brazil's dependence on imported fertilizers keeps the operation exposed to price and availability volatility. A prudent strategy combines productivity targets per plot (rather than generic farm targets), fertilization scenario simulations (conventional versus EEFs and/or organomineral fertilizers), and staggered purchases. Instead of "betting the farm" on a single technology, it is worth partially diversifying sources and testing in comparable areas, measuring cost per bag and soil attribute trends. This logic dilutes risks, protects cash flow, and maintains flexibility for adjustments during the harvest.

For all of this to work, it is worth adopting a minimum monitoring panel that fits on a single page. Per farm (or per management unit), monitor productivity per plot and its coefficient of variation, pH and V% in management zones, P and K levels, an annual reading of organic matter and, above all, three efficiency indicators: NUE, PUE and KUE, mapping how many kilograms of coffee are produced per kilogram of nutrient applied. Add to this the nutritional cost per bag and the application efficiency (planned versus applied). These are simple numbers, but they change the conversation: they allow you to compare strategies, justify technologies, and, above all, learn from one harvest to the next.

Execution throughout the phenological cycle can be lean and effective. In the post-harvest period, the focus is on recovering the plant, building roots and canopy for the next flowering: soil correction (liming and gypsum when indicated) and supply of N and K with sources and forms of lower loss. In the pre-flowering period, ensure pH and calcium in the profile and keep phosphorus available. During grain filling and ripening, potassium supports transport and quality; N management avoids late excesses that interfere with maturation. In the pre-harvest period, fertilizers that increase the risk of quality loss should be avoided, and efforts should focus on consolidating records and preparing for the next cycle. You will notice that none of this requires fancy technology, just order, timing, and consistency.

Finally, it is important to adjust the language to the audience that is dealing with this on a daily basis. For students, the focus should be on principles (why volatilization occurs, how phosphorus fixation works,

what changes in the load balance when pH is corrected) and measurement methods. For technicians, standardized sampling, interpretation, and recommendation protocols, as well as simple execution audits, make the difference between a plan “on paper” and management that changes results. For producers, the secret lies in choosing two or three innovations that fit the operation (for example, urea with urease inhibitor, recommendation in management zones, and a pilot with organomineral) and repeating them well, year after year, adjusting the course based on indicators.

Resilience, therefore, is not about collecting technologies, but about doing the essentials with precision and incorporating innovations that increase nutrient efficiency per bag produced, reduce losses in critical windows, and build a more living and stable soil. In an environment of uncertain climate and volatile inputs, this combination (quality diagnosis, efficient sources and forms, and soil treated as an asset) is what allows us to get through difficult harvests and fully capture the good ones, with productivity, quality, and sustainability going hand in hand.

FINAL CONSIDERATIONS

Soil fertility and mineral nutrition of coffee trees together represent one of the most decisive pillars for productivity, bean quality, and sustainability of the Brazilian coffee system. Throughout this book, we have sought to offer technical, up-to-date, and applicable content aimed at different reader profiles, whether field technicians, students in training, or coffee growers seeking greater autonomy and production efficiency.

It has become clear that the nutritional management of coffee crops cannot be treated in a generic or standardized manner. Each production environment has distinct edaphic, climatic, historical, and operational characteristics, requiring an integrated approach based on reliable diagnostics (chemical, physical, and biological soil analyses, as well as foliar analyses), application technology, agronomic planning, and scientific interpretation of results.

The responsible use of inputs, combined with regenerative practices such as green manure, the use of bio-inputs, rock dusting, and permanent soil cover, should be seen as not only a technical advance, but also an ethical and environmental one. The coffee farming of the future will necessarily be more efficient in its use of nutrients, more balanced in biological terms, and more committed to soil health, the producer's greatest natural asset.

By mastering the fundamentals of mineral nutrition and understanding soil dynamics, field professionals expand their decision-making capacity, reduce waste, and maximize economic returns. More than just applying fertilizers, it is about managing processes.

May this material serve as a technical basis, reference, and stimulus for the adoption of agronomically correct, economically viable, and ecologically sustainable practices. Soil is a living organism, and knowledge about it is the first step toward more resilient, profitable, and sustainable coffee farming.



ACKNOWLEDGMENTS

The organization of this book was only possible thanks to the direct and indirect contributions of various professionals, institutions, and experiences accumulated over the years in the field of agronomy and coffee farming.

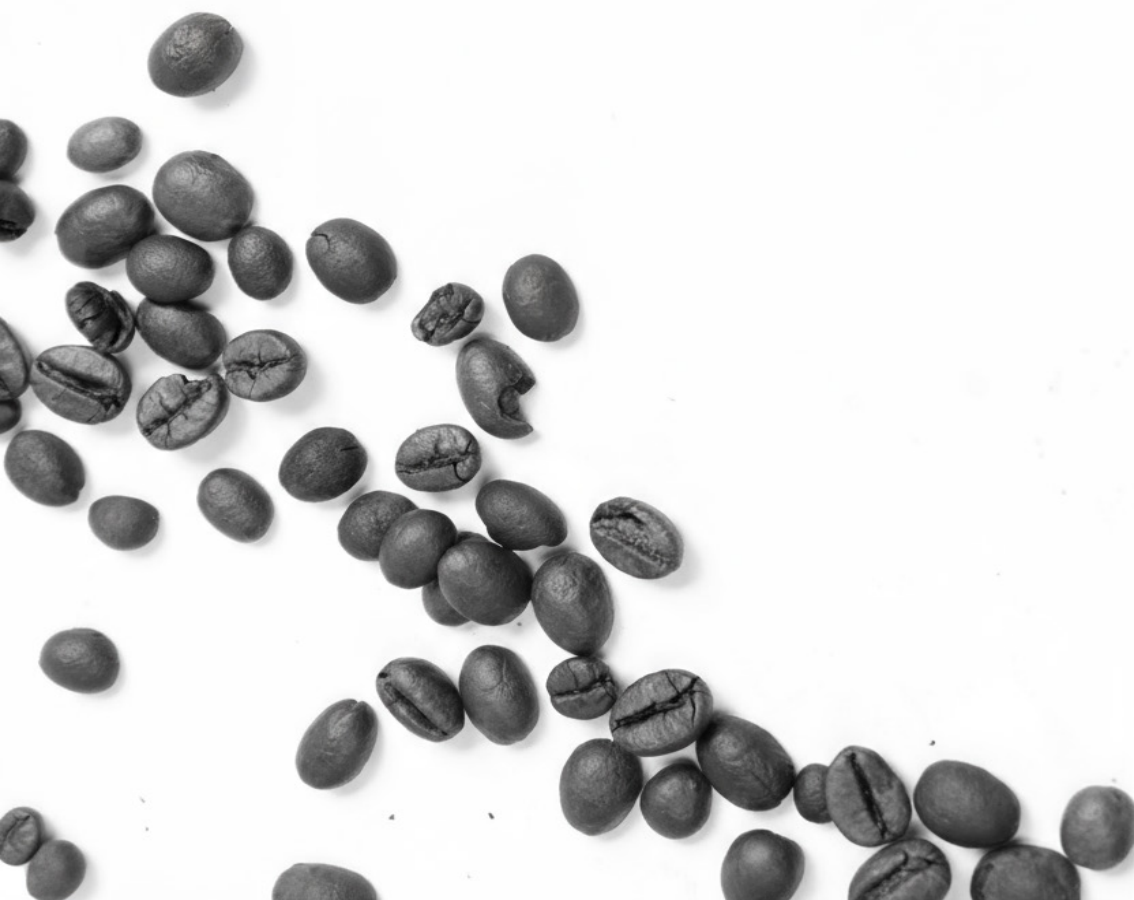
I would like to thank the researchers and extension agents who, through their tireless work, have promoted advances in the understanding of soil fertility and mineral nutrition in coffee trees.

The data presented here are based on national and international scientific publications, many of which come from institutions such as EMBRAPA Café, the Campinas Agronomic Institute (IAC), the Federal University of Lavras (UFLA), EPAMIG, and the Procafé Foundation, among others that strengthen agricultural research in Brazil.

I extend my gratitude to the coffee growers in various regions of the country, who are true living laboratories of innovation and sustainable management, whose practical experiences inspired the realistic approach adopted in this material.

I would also like to thank the teachers, students, and agricultural technicians (each with their own role) who, through education and technology transfer, keep alive the Brazilian coffee industry's vocation to produce with quality, responsibility, and agronomic excellence.

Finally, I dedicate this work to the new generation of professionals in the field, who seek to reconcile science and practice with ethics, precision, and respect for the soil and plants.



REFERENCES

- ALCARDE, J.C. & RODELLA, A.A. *Qualidade e legislação de fertilizantes e corretivos*. In: CURI, N.; MARQUES, J.J.; GUILHERME, L.R.G.; LIMA, J.M.; LOPES, A.S. & ALVAREZ V., V.H. eds. *Tópicos em ciência do solo*. Viçosa, MG, Sociedade Brasileira de Ciência do Solo, 2003. p.291-334.
- ALLOWAY, B. J. *Zinc in soils and crop nutrition*. 2. ed. Brussels: International Zinc Association; Paris: International Fertilizer Industry Association, 2008.
- ALVAREZ V., V.H.; NOVAIS, R.F. de; DIAS, L.E.; OLIVEIRA, J.A. *Determinação e uso do fósforo remanescente*. Boletim Informativo da Sociedade Brasileira de Ciência do Solo, v.25, p.27-32, 2000.
- ARAÚJO, L. G. et al. (2014). Organic matter fractions in soil under coffee with split applications of phosphorus and water regimes. *Revista Brasileira De Engenharia Agrícola E Ambiental*, 18(10), 1017–1022. <https://doi.org/10.1590/1807-1929/agriambi.v18n10p1017-1022>.
- BARROS, M. M.; VOLPATO, C. E. S.; SILVA, F. C.; PALMA, M. A. Z.; SPAGNOLO, R. T. Avaliação de um sistema de aplicação de fertilizantes a taxa variável adaptado à cultura cafeeira. *Coffee Science*, Lavras, v. 10, n. 2, p. 223–232, 2015.
- BATAGLIA, O. C.; FURLANI, A. M. C.; TEIXEIRA, J. P. F.; FURLANI, P. R.; GALLO, J. R. *Métodos de análise química de plantas*. Campinas: Instituto Agrônômico, 1983. 48 p. (Boletim Técnico, 78).
- BERTON, R. S.; PRATT, P. F.; FRANKENBERGER JR., W. T. Disponibilidade de fósforo estimada por três métodos químicos e pela atividade de duas enzimas em solos que receberam incorporação de materiais orgânicos. *Revista Brasileira de Ciência do Solo*, v. 21, n. 4, p. 617–624, 1997.
- BRONICK, C. J.; LAL, R. Soil structure and management: a review. *Geoderma*, Amsterdam, v. 124, p. 3-22, 2005.
- CAIRES, E. F., CHURKA, S., GARBUIO, F. J., FERRARI, R. A., & MORGANO, M. A.. (2006). *Soybean yield and quality a function of lime and gypsum applications*. *Scientia Agricola*, 63(4), 370–379.

- CAIRES, E. F.; GUIMARÃES, A. M. A Novel Phosphogypsum Application Recommendation Method under Continuous No-Till Management in Brazil. *Agronomy Journal* - Soil Fertility and Crop Nutrition, v. 110, n. 5, p. 1987-1995, 2018.
- C.E. CARDUCCI, G.C. OLIVEIRA, N. CURI, R.J. HECK, D.F. ROSSONI, T.S. DE CARVALHO, A.L. COSTA. *Gypsum effects on the spatial distribution of coffee roots and the pores system in oxidic Brazilian Latosol*, Soil and Tillage Research, v. 145, p. 171-180, 2015.
- CARDUCCI, C. E.; G. C. de OLIVEIRA (Org). *Manejo do solo na cafeicultura: produtividade e sustentabilidade*. Lavras: Editora UFLA, 2021, 135p.
- CARELLI, M.L.C. *et al. Aspects of nitrogen metabolism in coffee plants*. Braz. J. Plant Physiol., 18(1):9-21, 2006.
- CHAGAS, W.F.T. *et al. NITROGEN FERTILIZERS TECHNOLOGIES FOR COFFEE PLANTS*. Coffee Science, v. 14, n. 1, p. 55–66, 2019.
- CHANDON, E., NUALKHAO, P., VIBULKEAW, M. *et al. Mitigating excessive heat in Arabica coffee using nanosilicon and seaweed extract to enhance element homeostasis and photosynthetic recovery*. BMC Plant Biol 24, 1064 (2024).
- CHAVES, J.C.D. *Manejo do solo: adubação e calagem, antes e após a implantação da lavoura cafeeira*. Londrina: IAPAR, 2002. 36 p. (Circular 120).
- CLEMENTE, J. M., MARTINEZ, H. E. P., ALVES, L. C., FINGER, F. L., & CECON, P. R. (2015). Effects of nitrogen and potassium on the chemical composition of coffee beans and on beverage quality. *Acta Scientiarum. Agronomy*, 37(3), 297–305.
- DE SOUSA, T. R., DE CARVALHO, A. M., RAMOS, M. L. G., DE OLIVEIRA, A. D., DE JESUS, D. R., DA FONSECA, A. C. P., DA COSTA SILVA, F. R., DELVICO, F. M. D. S., JUNIOR, F. B. D. R., & MARCHÃO, R. L. (2024). *Dynamics of Carbon and Soil Enzyme Activities under Arabica Coffee Intercropped with Brachiaria decumbens in the Brazilian Cerrado*. Plants, 13(6), 835.
- DUTRA, M. P., SARKIS, L. F., OLIVEIRA, D. P., SANTIAGO, H. D. A., RESENDE, G. T. D. S., DE MELO, M. E. A., DA FONSECA, A. B., LÓPEZ, C. J. H., SILVA, E. D. S., ZAQUEU, A. D. S., DE LIMA, G. H. F., SILVA, J. M., POZZA, A. A. A., & GUELFI, D. (2025). Cutting-Edge

Technology Using Blended Controlled-Release Fertilizers and Conventional Monoammonium Phosphate as a Strategy to Improve Phosphorus Coffee Nutrition During the Coffee Development Phase. *Soil Systems*, 9(2), 47.

ECOFRIENDLY COFFEE. *Nitrogen economy inside coffee plantations*. 2023. Disponível em: <https://ecofriendlycoffee.org/nitrogen-economy-inside-coffee-plantations/>.

EMPRESA DE ASSISTÊNCIA TÉCNICA E EXTENSÃO RURAL DE MINAS GERAIS – EMATER-MG. *Manual do Café: Manejo de Cafezais em Produção*. Belo Horizonte: EMATER-MG, 2016.

EPSTEIN, E.; BLOOM, A. J. *Mineral nutrition of plants: principles and perspectives*. 2. ed. Sunderland: Sinauer Associates, 2005. 400 p.

FAGERIA, N.K., BALIGAR, V.C., & CLARK, R. (2006). *Physiology of Crop Production (1st ed.)*. CRC Press. <https://doi.org/10.1201/9781482277807>.

FAGERIA, N.K., BALIGAR, V.C., & JONES, C.A. (2010). *Growth and Mineral Nutrition of Field Crops (3rd ed.)*. CRC Press. <https://doi.org/10.1201/b10160>.

FAQUIN, V. *Nutrição mineral de plantas*. Lavras: UFLA, 2005. 186 p.

FARNEZI, M. M. DE M., SILVA, E. DE B., & GUIMARÃES, P. T. G.. (2009). Diagnose nutricional de cafeeiros da região do Alto Jequitinhonha (MG): normas dris e faixas críticas de nutrientes. *Revista Brasileira De Ciência Do Solo*, 33(4), 969–978. <https://doi.org/10.1590/S0100-06832009000400021>

FENILLI, T. A. B., REICHARDT, K., FAVARIN, J. L., BACCHI, O. O. S., SILVA, A. L., & TIMM, L. C.. (2008). Fertilizer 15N balance in a coffee cropping system: a case study in Brazil. *Revista Brasileira De Ciência Do Solo*, 32(4), 1459–1469. <https://doi.org/10.1590/S0100-06832008000400010>.

FERRAZ, G. A. E. S., SILVA, F. M. DA ., CARVALHO, F. DE M., COSTA, P. A. N. DA ., & CARVALHO, L. C. C.. (2011). Viabilidade econômica do sistema de adubação diferenciado comparado ao sistema de adubação convencional em lavoura cafeeira: um estudo de caso. *Engenharia Agrícola*, 31(5), 906–915. <https://doi.org/10.1590/S0100-69162011000500008>.

GUARÇONI, A. *Saturação por bases para o cafeeiro baseada no ph do solo e no suprimento de Ca e Mg*. Coffee Science, Lavras, v. 12, n. 3, p. 327–336, jul./set. 2017.

- LIMA FILHO, O. F. DE ., & MALAVOLTA, E.. (2003). Studies on mineral nutrition of the coffee plant (*Coffea arabica* L. cv. Catuaí Vermelho): LXIV. Remobilization and re-utilization of nitrogen and potassium by normal and deficient plants. *Brazilian Journal of Biology*, 63(3), 481–490.
- MALAVOLTA, E. *Manual de nutrição mineral de plantas*. São Paulo: Ceres, 2006. 631 p.
- MALAVOLTA, E.; VITTI, G. C.; OLIVEIRA, S. A. *Avaliação do estado nutricional das plantas: princípios e aplicações*. 2. ed. Piracicaba: POTAFOS, 1997. 319 p.
- MANCUSO, M. A. C., SORATTO, R. P., CRUSCIOL, C. A. C., & CASTRO, G. S. A.. (2014). Effect of potassium sources and rates on arabica coffee yield, nutrition, and macronutrient export. *Revista Brasileira De Ciência Do Solo*, 38(5), 1448–1456. <https://doi.org/10.1590/S0100-06832014000500010>.
- MARSCHNER, H. *Mineral nutrition of higher plants*. 3. ed. London: Academic Press, 2012. 651 p.
- MARTINEZ, H. E. P., CLEMENTE, J. M., LACERDA, J. S. DE ., NEVES, Y. P., & PEDROSA, A. W.. (2014). Nutrição mineral do cafeeiro e qualidade da bebida. *Revista Ceres*, 61, 838–848. <https://doi.org/10.1590/0034-737x201461000009>.
- MATIELLO, J. B.; SANTINATO, R.; GARCIA, A. W. R.; ALMEIDA, S. R.; FERNANDES, D. R. *Cultura do café no Brasil: manual de recomendações*. Varginha: Fundação Procafé, 2020. 716 p.
- MONICELLI, F., CUNHA, K. P. V. DA ., ARAÚJO, F., & BECKER, V.. (2021). Phosphorus sorption potential of natural adsorbent materials from a Brazil semiarid region to control eutrophication. *Acta Limnologica Brasiliensia*, 33, e29.
- MOREIRA, D.T. et al. Determination of physical and chemical quality of coffee beans under improved potassium fertilization managements. *Coffee Science*, v. 16, p. 1–10, 2021.
- MOTA, R. P. et al. Organomineral fertilizer in coffee plant (*Coffea arabica* L.): Fertilizer levels and application times. *Coffee Science*, Lavras, v. 18, p. e182098, 2023.

NASCIMENTO, M. O., COSTA CELESTINO, S. M., VEIGA, A. D., DE JESUS, B. D. A., & DE LACERDA DE OLIVEIRA, L. (2024). Quality of Arabica coffee grown in Brazilian Savannah and impact of potassium sources. *Food research international (Ottawa, Ont.)*, 188, 114500. <https://doi.org/10.1016/j.foodres.2024.114500>

NOVAIS, R. F. et al. *Fertilidade do solo*. Viçosa: SBCS, 2007.

NOVAIS, R. F.; SMYTH, T. J. *Fósforo em solo e planta em condições tropicais*. Viçosa: Universidade Federal de Viçosa, 1999. 399 p.

NUNES, R. DE S., SOUSA, D. M. G. DE ., GOEDERT, W. J., & VIVALDI, L. J.. (2011). Distribuição de fósforo no solo em razão do sistema de cultivo e manejo da adubação fosfatada. *Revista Brasileira De Ciência Do Solo*, 35(3), 877–888. <https://doi.org/10.1590/S0100-06832011000300022>.

OLIVEIRA, L. L., NASCIMENTO, M. O., & CELESTINO, S. M. C. (2025). Integrating optimized descriptive profile, consumer acceptance, and textual analysis to assess coffee beverage quality: Exploring potassium fertilization in Brazil's Central Plateau. *Food research international (Ottawa, Ont.)*, 212, 116525.

PARECIDO, R. J., SORATTO, R. P., GUIDORIZZI, F. V. C., PERDONÁ, M. J., & GITARI, H. I. (2021). Soil application of silicon enhances initial growth and nitrogen use efficiency of Arabica coffee plants. *Journal of Plant Nutrition*, 45(7), 1061–1071.

PAUL, E. A. et al. *Soil microbiology, ecology, and biochemistry*. 4. ed. Oxford: Academic Press, 2013, 603 p.

PAVINATO, P. S., & ROSOLEM, C. A.. (2008). Disponibilidade de nutrientes no solo: decomposição e liberação de compostos orgânicos de resíduos vegetais. *Revista Brasileira De Ciência Do Solo*, 32(3), 911–920.

PEREIRA, M. G., LOSS, A., BEUTLER, S. J., & TORRES, J. L. R.. (2010). Carbono, matéria orgânica leve e fósforo remanescente em diferentes sistemas de manejo do solo. *Pesquisa Agropecuária Brasileira*, 45(5), 508–514.

RAIJ, B. van.; CANTARELLA, H.; QUAGGIO, J.A. & FURLANI, A.M.C., eds. *Recomendações de adubação e calagem para o estado de São Paulo*. 2.ed. Campinas, Instituto Agrônômico/FUNDAG, 1997. 285p. (Boletim Técnico, 100).

RIBEIRO, A. C.; GUIMARÃES, P. T. G.; ALVAREZ V., V. H. (Eds.).

Recomendações para o uso de corretivos e fertilizantes em Minas Gerais: 5ª aproximação. Viçosa: CFSEMG, 1999. 359 p.

RODRIGUES, M. J. L., DA SILVA, C. A., BRAUN, H., & PARTELLI, F. L. (2023). Nutritional Balance and Genetic Diversity of *Coffea canephora* Genotypes. *Plants*, 12(7), 1451.

RODRIGUES, F. A., CARRÉ-MISSIO, V., JHAM, G. N., BERHOW, M., & SCHURT, D. A.. (2011). Chlorogenic acid levels in leaves of coffee plants supplied with silicon and infected by *Hemileia vastatrix*. *Tropical Plant Pathology*, 36(6), 404–408.

SANTOS, C., MALTA, M. R., GONÇALVES, M. G. M., BORÉM, F. M., POZZA, A. A. A., MARTINEZ, H. E. P., DE SOUZA, T. L., CHAGAS, W. F. T., DE MELO, M. E. A., OLIVEIRA, D. P., LIMA, A. D. C., DE ABREU, L. B., REIS, T. H. P., DE SOUZA, T. R., BUILES, V. R., & GUELFI, D. (2023). Chloride Applied via Fertilizer Affects Plant Nutrition and Coffee Quality. *Plants*, 12(4), 885.

SANTOS, D. R. DOS ., GATIBONI, L. C., & KAMINSKI, J.. (2008). Fatores que afetam a disponibilidade do fósforo e o manejo da adubação fosfatada em solos sob sistema plantio direto. *Ciência Rural*, 38(2), 576–586. <https://doi.org/10.1590/S0103-84782008000200049>.

SILVA, É. A. DA ., OLIVEIRA, G. C. DE ., SILVA, B. M., CARDUCCI, C. E., AVANZI, J. C., & SERAFIM, M. E.. (2014). Aggregate stability by the “high energy moisture characteristic” method in an oxisol under differentiated management. *Revista Brasileira De Ciência Do Solo*, 38(5), 1633–1642.

SILVA, E. DE B., NOGUEIRA, F. D., GUIMARÃES, P. T. G., CHAGAS, S. J. DE R., & COSTA, L.. (1999). Fontes e doses de potássio na produção e qualidade do grão de café beneficiado. *Pesquisa Agropecuária Brasileira*, 34(3), 335–345. <https://doi.org/10.1590/S0100-204X1999000300003>.

SOUSA, D. M. G.; LOBATO, E. (Eds.). *Cerrado: correção do solo e adubação*. 2. ed. Planaltina: Embrapa Cerrados, 2004. Cap. “Correção da acidez do solo”, p. 81–96.

SOUZA, R. F. DE ., FAQUIN, V., TORRES, P. R. F., & BALIZA, D. P.. (2006). Calagem e adubação orgânica: influência na adsorção de fósforo em solos. *Revista Brasileira De Ciência Do Solo*, 30(6), 975–983.

TAIZ, L. et al. *Fisiologia e desenvolvimento vegetal*. 7. ed. Porto Alegre: Artmed, 2021. 888 p.

TISDALL, J.M. and OADES, J.M. (1982), *Organic matter and water-stable aggregates in soils*. Journal of Soil Science, 33: 141-163.

VALADARES, S. V., NEVES, J. C. L., ROSA, G. N. G. P., MARTINEZ, H. E. P., VENEGAS, V. H. A., & LIMA, P. C. DE .. (2013). Produtividade e bienalidade da produção de cafezais adensados, sob diferentes doses de N e K. *Pesquisa Agropecuária Brasileira*, 48(3), 296–303.

