ISSN 2176-2937

Documentos 470

Londrina, PR / February, 2025

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Embrapa Soja

Empresa Brasileira de Pesquisa Agropecuária
Embrapa Soja
Ministério da Agricultura e Pecuária

ISSN 2176-29370

Documentos 470

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Embrapa Soja
Londrina, PR
2025

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Document originally published under the title “Tecnologias de manejo da fertilidade do solo e avaliação do estado nutricional da soja”, 2023. (Embrapa Soja. Documentos, 458).

Cataloging in Publication (CIP)
Embrapa Soja

Soil fertility management technologies and nutritional status assessment of soybeans / Fábio Alvares de Oliveira ... [et al.]. – Londrina : Embrapa Soja, 2025.
83 p. (Documentos / Embrapa Soja, ISSN 2176-2937 ; n. 470).

1. Manejo do solo. 2. Soja. I. Oliveira, Fábio Alvares de. II. Castro, César de. III. Oliveira Junior, Adilson de. IV. Klepker, Dirceu. V. Firmano, Ruan Francisco. VI. Série.

CDD 631.8 (21. ed.)

Valéria de Fátima Cardoso (CRB 9/1188)

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Presentation

This publication brings together a set of technical information extracted from the results of experimental research and investigation in commercial crops with nutritional disorders, obtained by the team of the SEG 20.18.03.067 FertSoja project, in several production environments, cultivated with soybean crops in the summer in succession with grain crops, especially wheat, corn and sunflower. Regional technical recommendation and bibliographic references on the subject, updated by several research institutions, are also presented.

Despite advances in knowledge of soil management technologies to reduce limiting factors and increase production capacity, and even with the high cost of fertilizers, planning errors and low fertilization efficiency have often resulted in nutrient imbalances that negatively affect yield, characterized by hidden hunger and even the appearance of visual symptoms.

The efficiency of fertilizers and the response to soybean fertilization are highly dependent on climatic factors, rainfall volume and distribution, and the physical, chemical and biological properties of the soil. The information available in this publication aims to demonstrate that correct fertilization management is regionalized and involves a set of criteria and indicators, associated with the production environment (soil and weather) and the best cultural practices, which determine greater production efficiency.

Alexandre Lima Nepomuceno
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Table of contents

Introduction

In recent years, soybean yields in Brazil have increased, not only due to the greater genetic potential of new commercial cultivars but also because of improvements in the agricultural production environment, particularly in managing the chemical, physical, and biological fertility of soils, which enhances nutrient availability and reduces limiting factors for root development. That increase in yield levels requires higher quantities of fertilizers and more balanced fertilizations that considering the nutrients requirements and their balance relationships. Thus, improvement of technical evaluations is essential to enable proper fertilization management, rationalizing fertilizer use for greater responses.

However, yield losses frequently occur due to the incorrect application of modern soil fertility management concepts, misinterpretation or underutilization of soil analyses, and lack of interest in adopting plant tissue analysis, resulting in reduced efficiency of applied fertilizers and nutritional imbalances.

Another important issue is that fertilizers significantly impact production costs, affecting the crop's profitability. Therefore, for the economic success of agricultural activities and environmental sustainability, in addition to selecting high-potential genetic materials adapted to each region, it is essential to understand soil fertility principles and apply technologies and adopt the fertilizer best management practices as a strategy for increasing productivity.

To achieve this, soil sampling must be representative from each environment and management condition, as the first step for a precision diagnosis and correction of soil fertility problems. Foliar analysis serves as a complementary approach to interpreting soil analyses, capable of more precisely identifying the nutrients limiting soybean productivity.

Finally, the basis for increasing productivity and sustainability in soybean production systems should be the establishment of integrated strategies that maintain and even enhance soil fertility, focusing on developing and improving soil management techniques and using cover crops, which are essential for improving soil profiles, root development, nutrient cycling and balance, and water conservation in the soil.

Soil Sampling

Sampling is the first and primary step in a soil fertility evaluation program and fertilization management, as the interpretation of chemical analysis results determines the possible rates of amendments and fertilizers to be applied.

Soil sampling for fertilization recommendations should be conducted during the largest available window between crops in production systems. In Brazil, this occurs during August and September for the soybean/corn system in central region and in March and April for the soybean/ wheat system in the southern region of the country. Sampling planning begins by dividing the agricultural fields into homogeneous areas concerning soil classes and attributes, topography, and the history of cultivation and fertilization. To ensure representativeness, sampling should consist of 10 to 20 simple sub-samples collected at randomly distributed points in each area. The set of sub-samples should be homogenized and placed in a labeled plastic bag, resulting in a composite sample of approximately 500 g, which should be quickly sent to the laboratory, avoiding long storage periods under humidity and high temperatures.

In the case of sampling to obtain maps of spatial variability of soil chemical attributes and apply precision agriculture, special attention should be paid to the sampling plan, in addition to agronomic criteria, Geostatistical principles also need to be fully met.

The top layer of soil, usually the 0–20 cm fraction, should be sampled because it is the most intensively explored by roots and chemically altered by management due to the applications of correctives and fertilizers and the direct action of crop residue cycling. In areas with a history of broadcasting and surface fertilization, which show higher vertical variability, stratified sampling is recommended for 0–10 cm and 10–20 cm. Additionally, subsurface sampling of the 20–40 cm layer is indicated to assess acidity at depth and monitor the availability of exchangeable bases, the presence of toxic aluminum (Al), and sulfur (S) accumulation.

Annual soil sampling frequency is ideal for monitoring and managing soil fertility. However, in intensively cultivated areas under succession/rotation or those with intercropping with cover crop species, the historical monitoring of soil fertility can be quite useful for adjusting the most appropriate sampling interval to plan soil management actions.

Correction of Soil Acidity

Nutrient availability is determined by various factors, including the soil's acidity, which represents the potential activity of hydrogen ions in the soil solution (pH). The variation in nutrient availability and toxic Al to plants based on soil pH (Figure 1) results from increased or decreased solubility of available forms present in the soil, biological activity on organic fractions, and cation exchange capacity (CEC), due to the predominance of pH-dependent charges in tropical soils. Generally, the acidity condition that promotes the highest availability and uptake of soil nutrients, as well as the precipitation of toxic Al, occurs within the pH (H_2O) range of 6.0 to 6.8.

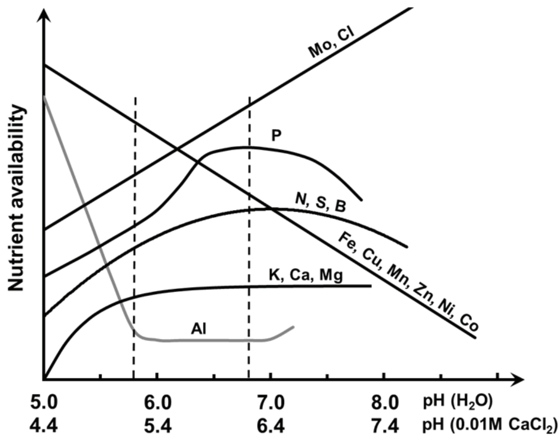

Figure 1. Relationship between pH and nutrient and aluminum availability in soil (adapted from Malavolta, 1980).

Liming

The negative impacts of acidity on agricultural crops date back to ancient times, even though they were not fully understood at that time. There are records of the application of marl (a type of limestone containing 35% to 60% clay) in soils of ancient Greece to improve soil quality and crop productivity (Fussell, 1959). Despite advances in soil chemistry, the problem persists today, with estimates suggesting that 30% of the Earth's surface is covered by acidic soils (pH < 4.5), equivalent to approximately 4 billion hectares (Sumner et al., 2003). In tropical South America, the proportion is even higher, reaching around 85% of naturally acidic soils due to intense weathering (Fageria et al. 2011), associated with active soil formation factors (Dokuchaev, 1883). In addition to low pH values, the presence of toxic aluminum (Al) is another factor that drastically limits productivity in tropical regions. Therefore, the most effective means of neutralization is through the application of acidity correctives like limestone, known as liming.

Liming is carried out based on the results of soil chemical analysis. Strictly speaking, the recommendation for limestone should consider the soil acidity level, buffering capacity (the soil's ability to resist changes in pH), and the type of production system adopted. Additionally, the effectiveness of liming also depends on the quality of the limestone, primarily determined by the Neutralizing Index (NI) and the chemical composition of the corrective, as well as the method of application, the amounts applied, and the reaction time, among other factors. These factors influence the residual effect of liming; therefore, soil chemical analysis should be conducted periodically to make decisions regarding the need for reapplication of the corrective. Figure 2 presents the critical levels of calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}) that must be achieved through acidity management and fertilization to avoid productivity limitations due to nutritional factors.

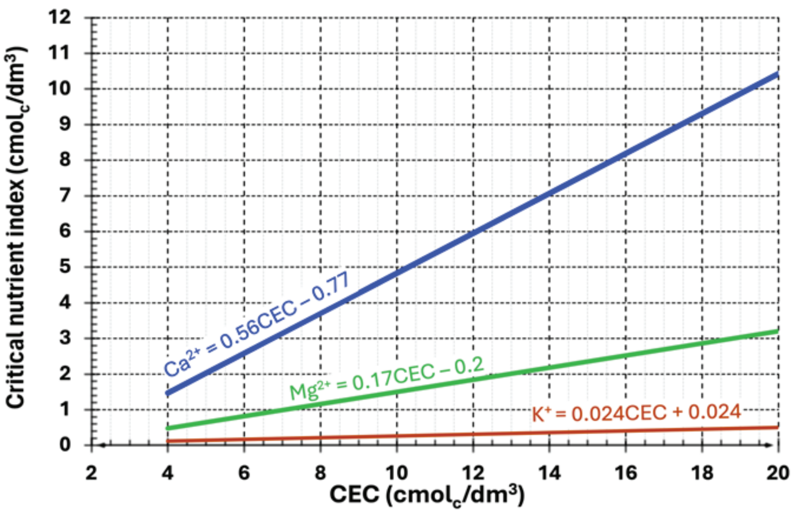

Figure 2. Critical levels of calcium, magnesium, and potassium in soils based on Cation Exchange Capacity (CEC).

Liming recommendation methods

There are various methods employed to estimate the need for limestone to correct soil acidity. Most formulas consider the top layer of 0–20 cm. Regarding incorporation, certain methods assume that the soil will be tilled, especially those developed before the expansion of the no-tillage (NT) system. In Brazil, three methods have been validated and are recommended for use in various agricultural regions.

a) Base saturation method

This method involves determining the amount of corrective needed to raise the soil pH, using the increase in base saturation as a reference, which has a positive correlation with pH value (V%) (Quaggio and Raij, 2022). The formula was initially proposed by Quaggio (1983) and is based on the works of Vageler (1932), Catani and Gallo (1955), and Malavolta (1976).

The calculation of the liming need (LN) is done using the formula:

$$LN\ (t/ha) = \frac{(V_2 - V_1) \times CEC}{NI}$$

where:

V_2 = target base saturation value (%);

V_1 = base saturation value of the soil before correction (%), in the 0–20 cm layer;

[V_1 = (SB/CEC) x 100], where, SB = Ca^{2+} + Mg^{2+} + K^+ ($cmol_c/dm^3$);

CEC = Cation Exchange Capacity ($cmol_c/dm^3$);

CEC = SB + H+Al ($cmol_c/dm^3$);

NI = Neutralizing Index

Due to the chemical (mineralogy) and physical (% clay) characteristics of soils predominant in Brazil, there is variation in the appropriate value of base saturation (V2), corresponding to the ideal pH range that determines the highest agronomic yield. Generally, for grain cultivation, the goal is to raise base saturation to 50% in low CEC soils and up to 70% in higher CEC soils. In pastures, which show greater tolerance to acidity, reference values may be lower, around 60%.

In general, in regions using the determination of potential acidity (H+Al) by the 0.5 M calcium acetate method or its estimation by the SMP index, the buffering capacity of the soils is often underestimated (Kaminski et al., 2002), particularly in sandy and low CEC soils, resulting in lower calculated values for LN and, therefore, less correction of acidity indicated by the achieved pH values.

b) Balance of soil Ca and Mg saturation method

Popularized by the paper of Albrecht (1975), this method is based on an ideal balance of the soil's exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}). The initial studies that laid the groundwork for the concept of cation relationships were conducted in New Jersey, USA (Bear et al., 1945; Bear and Toth, 1948; Hunter, 1949; and Prince et al., 1947). Generally, the method suggests that about 50-60% of the cation exchange complex should be occupied by Ca, 10-15% by Mg, and 2-5% by K. Below are two equations: the first based on Ca levels and the second on Mg levels, for increasing the saturation of either cation in the exchange complex to predetermined values of 60% Ca^{2+} or 15% Mg^{2+}.

$$CaO\ (t/ha) = [(CEC \times 0.6) - Ca] \times 0.561$$

$$MgO\ (t/ha) = [(CEC \times 0.15) - Mg] \times 0.404$$

where:

CEC = Cation Exchange Capacity ($cmol_c/dm^3$);

Ca or Mg = Calcium or magnesium exchangeable contents ($cmol_c/dm^3$);

It is important to note that the cation proportions cited were determined for soils of different nature than those commonly found in tropical regions like Brazil. Moreover, the studies aimed to identify the ideal condition for alfalfa cultivation, which has higher nutritional demands than grain, soybean, or corn crops. When the critical sufficiency levels in the soil are met, soybean plant development is not limited by the (Ca + Mg)/K ratio over a wide range of variation. However, significant imbalances should be corrected when values exceed ~35 (Mascarenhas et al., 1987; Rosolem et al., 1992), as productivity losses in soybeans are associated with potassium deficiency induced by imbalances with divalent cations. Recent studies have shown little to no effect of cation ratios on the productivity of major agricultural crops, contradicting the foundation of this method (Chaganti and Culman, 2017). Thus, the balance among bases should be used as a qualitative criterion for defining the type of corrective to be used.

c) Neutralization of Al and supply of Ca and Mg method

This method is particularly suitable for soils under *Cerrado* vegetation, especially those with low CEC where both effects are important (Alvarez V; Ribeiro, 1999). The calculation of liming need (LN) includes, in addition to characteristics related to the soil's buffering capacity (Y), the crop requirements, such as the tolerated saturation of Al^{3+} (mt) and the minimum requirement for Ca^{2+} + Mg^{2+}.

$$LN\ (t/ha) = Y \times \left[Al^{3+} - \left(m_t \times \frac{CECe}{100}\right)\right] + [2 - (Ca^{2+} + Mg^{2+})]$$

where:

Y = soil acidity buffering capacity, estimated from clay content or remaining phosphorus value (P-rem):

Y = 0.0302 + 0.06532 x Clay – 0.000257 x Clay^2

Y = 4.002 – 0.125901 x P-rem + 0.001205 x P-rem^2 – 0.00000362 x P-rem^3

Al^{3+} = exchangeable aluminum ($cmol_c/dm^3$);

m_t = aluminum saturation tolerated by the crop and/or production system;

CEC_e = effective cation exchange capacity of the soil, em $cmol_c\ dm^{-3}$

Ca^{2+} = exchangeable calcium ($cmol_c/dm^3$)

Mg^{2+} = exchangeable magnesium ($cmol_c/dm^3$)

d) SMP index method

Based on the studies of Shoemaker, McLean, and Pratt (1961), the method relies on pH values obtained after equilibrating the soil with a buffer solution. After obtaining the SMP index, one should consult the reference table (Table 1) that contains the necessary amounts of limestone to raise the pH (H_2O) to a desired value. During the reaction, soils with higher potential acidity will require more limestone due to their higher buffering capacity. Its use has been more widespread in the states of Rio Grande do Sul and Santa Catarina, as for soils with lower CEC and buffering capacity, which require smaller limestone rates, the method does not perform well (Raij et al., 1979).

The amount of corrective indicated to raise the soil pH (H_2O) to 5.5 or 6.0 is determined based on the SMP index value of the soil (Table 1). These rates were established for the 0–20 cm layer and for limestones with a NI of 100. They should be adjusted according to the soil layer to be corrected and the NI value of the corrective.

Table 1. Amount of limestone needed to raise soil pH (H_2O) to 5.5 to 6.0

SMP index	target pH (H_2O)		SMP index	target pH (H_2O)	
	5.5	6.0		5.5	6.0
	t/ha(1)			t/ha(1)	
≤4.4	15.0	21.0	5.8	2.3	4.2
4.5	12.5	17.3	5.9	2.0	3.7
4.6	109	15.1	6.0	1.6	3.2
4.7	9.6	13.3	6.1	1.3	2.7
4.8	8.5	11.9	6.2	1.0	2.2
4.9	7.7	10.7	6.3	0.8	1.8
5.0	6.6	9.9	6.4	0.6	1.4
5.1	6.0	9.1	6.5	0.4	1.1
5.2	5.3	8.3	6.6	0.2	0.8
5.3	4.8	7.5	6.7	0.0	0.5
5.4	4.2	6.8	6.8	0.0	0.3
5.5	3.7	6.1	6.9	0.0	0.2
5.6	3.2	5.4	7.0	0.0	0.0
5.7	2.8	4.8	-	-	-

(1) Amount of acidity corrective with 100 of NI for the 0–20 cm soil layer. Source: Manual... (2016).

In some soils, especially sandy ones with low buffering capacity, the SMP index may indicate very small amounts of corrective or even suggest that acidity correction is unnecessary, even though the pH (H_2O) value may be below the minimum recommended for the crop. In these soils, the need for liming is calculated based on the levels of organic matter (OM) and exchangeable aluminum (Al^{3+}) in the soil, using the following equations to achieve the desired pH (H_2O):

to pH **5.5**: *Lime Rate = - 0.653 + 0.480 OM + 1.937* Al^{3+}*;*
to pH **6.0**: *Lime Rate = - 0.516 + 0.805 OM + 2.435* Al^{3+}*;*

where, Lime Rate is expressed in t/ha; OM in % and Al^{3+} in $cmol_c\ dm^{-3}$.

Time and methods of limestone application

Before implementing the no-tillage, in acidic soils managed under conventional tillage or natural field conditions, it is recommended to correct at least the acidity of the arable layer (0–20 cm) as described, through the incorporation of limestone based on the mentioned criteria.

In soils under a consolidated no-tillage system, surface liming is recommended when the pH (H_2O) value of the 0–20 cm layer is less than 5.5, the base saturation value is at least 10% lower than the reference value (50–70%), or the aluminum saturation higher than 20%. These criteria consider that acidity correction was performed at depths higher than 10 cm during the implementation of the system and that reacidification of soils managed without tilling occurs from the surface. Under these conditions, acidity correction can be gradual, with the surface application of limestone in installments, achieving results equivalent to total correction (Oliveira et al., 2023), as shown in Figure 3.

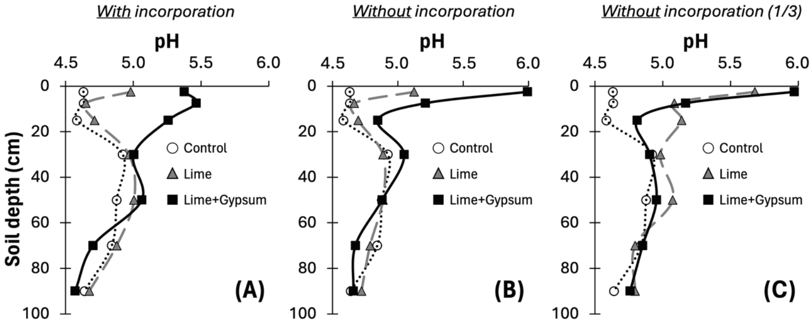

Figure 3. Soil profile acidity in response to forms of limestone application. Sub-figures: Amendments applied to the soil surface, **with** incorporation up to 25 cm (**A**); and **without** incorporation (**B**) with total rates (6 t/ha of lime and 6 t/ha of gypsum) applied only in the first year; amendments applied to the soil surface **without** incorporation (**C**) with the total rate split into three years (2 t/ha of lime and 2 t/ha of gypsum applied each year, three times). Source: (Oliveira et al., 2023).

In soils with acidity and aluminum saturation ≥ 25% in the 0–20 cm layer, it may be necessary to restart the no-tillage system. This is particularly important in areas where crop productivity is below the local average, especially in dry years, where soil compaction restricts root growth and phosphorus availability is low. In this situation, stratified soil sampling (0–10 cm, 10–20 cm) is recommended. If the decision is made to restart the no-tillage system, the average values from the samples at both depths should be considered for calculating and applying the highest recommended limestone rates based on regional criteria, incorporated with a heavy harrow. Care should be taken to restart the no-tillage system and carry out mechanized operations under ideal weather and soil moisture conditions, among other reasons, to prevent soil loss due to erosion. In soils under a consolidated no-tillage system, with recent liming, when soil analysis indicates that one of the liming decision criteria has not been met, the application of corrective will not necessarily increase soybean yield. This is because the SMP method does not detect the corrective that has not yet reacted in the soil. Generally, three years are needed for complete dissolution of the corrective to occur.

Limestone quality and use

Several basic conditions must be observed to achieve the liming goals of neutralizing exchangeable aluminum and/or increasing calcium and magnesium levels:

• The limestone must pass 100% through a 2 mm sieve;

• The limestone must contain CaO + MgO levels > 38%;

• The choice of limestone should consider the exchangeable levels of calcium and magnesium as well as the Ca/Mg ratio in the soil. In soils with low to medium Mg^{2+} levels, or when the Ca/Mg ratio is high, preference should be given to limestone with a higher MgO content, above 12%;

• Uneven distribution increases the spatial variability of soil acidity-related attributes and promotes nutritional imbalances.

Purchase decision

In regions with greater diversity of acidity correctives available, the choice should be based on the source that offers the best cost/benefit. There is a simple formula that can be used to determine which limestone represents the best financial decision for the agricultural enterprise, with the understanding that the lower the **Purchase Factor** (**PF**), the better the cost/benefit of the corrective.

$$Purchase\ Factor\ (\boldsymbol{PF}) = \frac{CP + SP}{NI}$$

where:

CP = Corrective price;

SP = Shipping price (R$/km x distance in km);

NI = Neutralizing Index.

Gypsum requirement

Agricultural soils can exhibit limitations due to subsurface acidity, as the effects of liming are more effective in the topsoil layer. Thus, deeper soil layers (below 20 cm) may show toxicity from exchangeable aluminum (Al^{3+}), even in soils that have been adequately corrected up to 20 cm. This issue can limit productivity, especially in regions where dry spells are more frequent or in second-crop cultivations. In this situation, the use of agricultural gypsum ($CaSO_4 \cdot 2H_2O$) is recommended to control aluminum toxicity in the subsurface.

Gypsum is considered a soil amendment because it does not alter the soil's acidity values (pH). However, agricultural gypsum has about 150 times the solubility of limestone, and the sulfate anion (SO_4^{2-}) is highly mobile in the soil profile, promoting the complexation of toxic Al^{3+}. Additionally, there is an increase in the levels of Ca^{2+} and sulfur (S) in the subsurface, resulting in a less limiting environment for root development. Thus, as a decision-making strategy, gypsum should be recommended in areas where **soil analysis in the 20-40 cm layer indicates an Al^{3+} saturation greater than 20% or when Ca^{2+} levels are below 0.5 cmolc/dm³**.

The need for gypsum (GN) can be calculated based on the clay content in the soil, using the equation below (Sousa; Lobato, 2004):

Additionally, there is a method based on base saturation (V) and CEC in the subsurface (Demattê, 1986; Vitti et al., 2008), expressed by the following equation:

$$GN\ (t/ha) = \frac{(V2 - V1) \times CEC}{500}$$

where:

V_2 = target base saturation value (%);

V_1 = base saturation value of the soil before correction (%) in the 20–40 cm layer;

CEC = Cation Exchange Capacity (cmolc/dm³) in the 20–40 cm layer.

More specifically for the southern region, the gypsum application can be calculated based on the saturation of Ca in the effective Cation Exchange Capacity (CECe) when the value is below 50%. Thus, the method is based on raising the calcium saturation (%Ca/CECe) of the subsurface layer of 20–40 cm to 60% (Caires; Guimarães, 2018).

$$GN\ (t/ha) = (0.6 \times CECe - Ca) \times 6.4$$

where:
CECe = effective CEC (Ca + Mg + K + Al)
Ca^{2+} = exchangeable calcium in $cmol_c/dm^3$
0.6 = target calcium saturation in the CECe
6.4 = constant generated by statistical adjustment

Notwithstanding the effectiveness of gypsum application, it is important to pay attention to the quantities applied, considering the comprehensive management of fertility and nutrient balance. High rates of gypsum, especially in soils with low CEC, can lead to imbalances due to the significant increase in Ca content, making it difficult for plants to uptake other cations such as K and, especially, Mg (item 5.3).

Mineral Requirements and Nutritional Status Assessment

Mineral requirements

Nutrient absorption is determined by genetic, edaphic, and environmental factors related to the total shoot dry matter production (TSDM) and the concentration of nutrients in the plant. Table 6 presents the average amounts of nutrients accumulated by the shoots and exported by soybean grains (Oliveira Junior et al., 2020).

However, due to genetic variation among cultivars in the Apparent Harvest Index (AHI = dry matter of grains/total dry matter) and the dilution/concentration effect of nutrients, greater amounts absorbed do not necessarily result in increased grain productivity. The quantities exported (Table 2) are directly proportional to productivity and nutrient concentration in the grains.

Therefore, replenishing the exported nutrients is also an essential criterion for recommending soybean fertilization and maintaining soil nutrient availability at adequate levels.

Table 2. Average quantities of nutrients **Accumulated** and **Exported** by the soybean.

Plant part	Nutrient										
	N	P[\4]	K[\4]	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	-------------- kg/ha --------------						-------------- g/ha --------------				
Grains[\2]	187	16.6	61	10	9	9.5	106	39	223	135	142
Crop residues	83	6.8	104	66	28	4.9	177	29	106	545	116
Total[\3]	270	23.4	165	76	37	14.4	283	68	128	680	258
% Exported	69	71	37	13	24	66	38	58	17	20	55
	------------ kg/t of grains ------------						--------- g/t of grains ---------				
Grains[\2]	54	4.8	18	2.8	2.5	2.8	31	11.5	65	39	41
Crop residues	24	2.0	30	19.3	8.2	1.4	51	8.3	310	159	34
Total	78	6.8	48	22.1	10.7	4.2	82	19.8	375	198	75

[\1.] Quantity of nutrients contained in the grains of the plants at the final development stage (R8, full maturity) – **Water base 13%.**

[\2.] Quantity of nutrients contained in the plant tissue at the Maximum Dry Matter Accumulation stage (R6).

[\3.] Conversion factors: P ➔ P_2O_5 = 2.29; K ➔ K_2O = 1.21.

Leaf diagnosis

The assessment of the nutritional status of plants is a method of interpretation based on the correlation between nutrient concentrations in plants and the yield potential of soybeans. Newly matured leaves are used to represent the nutritional status of soybeans, and for this reason, the technique is known as leaf diagnosis. Leaf sampling for chemical analysis should be conducted during the early flowering stages (Fehr; Caviness; 1977), collecting the third or fourth trifoliate leaf, with or without petiole, identified from the apex of the plants. To ensure the representativeness of the plot, the sample must consist of leaves from at least 25 plants, free from dust or contamination from spray products.

After collection, the leaves should be placed in paper bags for drying and sent to the analysis laboratory. The ideal time for leaf sampling varies depending on the growth habit. The developmental stage of approximately 50% of the plants in the plot should be considered. For determinate growth cultivars, sampling should occur from the beginning of flowering to full flowering (Stages R1 to R2). On the other hand, the phenological stage for leaf sampling of indeterminate growth cultivars is R2, which can extend to the beginning of stage R3, provided that the plants are in the vegetative stage V8/V10 (Figure 4).

Leaf diagnosis of soybeans with indeterminate growth habit

- Sampling should be done **starting from V8**, provided that at least 50% of the plants are in R2/R3 (flowers at the 1st and/or 2nd upper node with expanded leaves)
- Collect the **third or fourth leaf** from the top down on the main steam (25 to 30 plants per plot)

Definitions – Fehr and Caviness (1977)

- **V8:** plants with 7 fully developed trifoliate leaves or 8 nodes.
- **R2**: plants with one open flower at one of the Upper nodes of the main stem.
- **R3**: plants with pods (0.5 to 2.0 cm) at one of the Upper nodes of the main stem.

Foto: Cesar de Castro

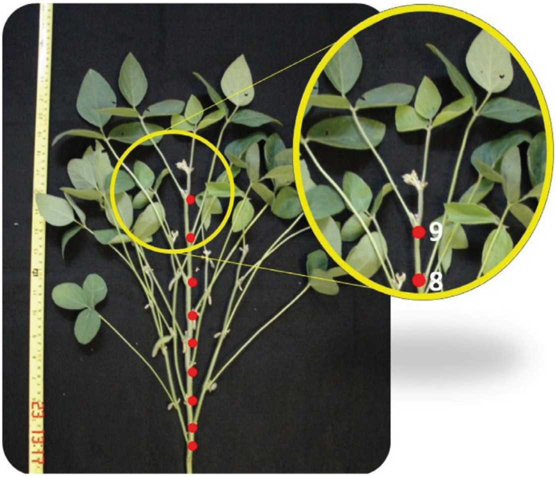

Figure 4. Soybeans with ten nodes on the main stem (V9), in reproductive stage R3.

Annex 1 presents the development stages of soybeans with determinate and indeterminate growth habits (Oliveira Junior et al., 2016).

Leaf nutrient levels are classified in relation to sufficiency levels or used for calculating nutritional balance indices (Castro et al., 2003). Table 3 presents the nutrient levels used for interpreting leaf analysis of soybeans without petiole.

Table 3. Classes and levels of nutrients used in the interpretation of leaf analysis results for soybeans **without petiole**.

Element	Low	Sufficient	High
		g/kg	
N	< 45.0	45.0 - 65.0	> 65.0
P	< 2.8	2.8 - 4.5	> 4.5
K	< 18.0	18.0 - 25.0	> 25.0
Ca	< 6.0	6.0 - 10.0	> 10.0
Mg	< 2.8	2.8 - 5.0	> 5.0
S	< 2.4	2.4 - 4.0	> 4.0
		mg/kg	
B	< 40	40 - 60	> 60
Cu	< 6	6 - 12	> 12
Fe	< 90	90 - 180	> 180
Mn	< 70	70 - 150	> 150
Zn	< 30	30 - 45	> 45

In Table 4, the sufficiency ranges of nutrients defined for indeterminate growth habit soybeans cultivated in the state of Paraná are presented.

Table 4. Nutrient levels used in the interpretation of leaf analysis results for indeterminate growth habit soybeans **without petiole** in Paraná state, Brazil.

Element	Low	Sufficient	High
		g/kg	
N	< 46	46 - 60	> 60
P	< 3.0	3.0 - 4.1	> 4.1
K	< 17.5	17.5 - 23	> 23
Ca	< 6.0	6.0 - 9.5	> 9.5
Mg	< 3.0	3.0 - 4.5	> 4.5
S	< 2.2	2.2 - 3.2	> 3.2
		mg/kg	
B	< 45	45 - 75	> 75
Cu	< 5.5	5.5 - 11	> 11
Fe	< 80	80 - 175	> 175
Mn	< 100	100 - 170	> 170
Zn	< 35	35 - 55	> 55

Source: Oliveira Junior et al. (2020).

For the state of São Paulo, leaf sampling should be conducted at full flowering (R2), collecting the 3rd leaf with petiole from 30 plants. The leaf diagnosis should be interpreted based on the reference values presented in Table 5.

Table 5. Adequate nutrient levels for soybean cultivation in the state of São Paulo for leaves **with petiole** collected at full flowering (R2).

Element	Low	Sufficient	High
		------------------------ g/kg ------------------------	
N	< 40	40 - 54	> 54
P	< 2.5	2.5 - 5.0	> 5.0
K	< 17	17 - 25	> 25
Ca	< 4	4 - 20	> 20
Mg	< 3	3 - 10	> 10
S	< 2.1	2.1 - 4.0	> 4.0
		------------------------ mg/kg ------------------------	
B	< 21	21 - 55	> 55
Cu	< 10	10 - 30	> 30
Fe	< 50	50 - 350	> 350
Mn	< 20	20 - 100	> 100
Mo	< 1.0	1.0 - 5.0	> 5.0
Zn	< 20	20 - 50	> 50

Source: Quaggio et al. (2022).

For the states of Mato Grosso do Sul and Mato Grosso, the interpretation of leaf analysis results is performed on samples collected at stage (R2), from the third or fourth trifoliate leaves, with or without petiole (Table 6).

Table 6. Nutrient levels used in the interpretation of leaf analysis results for soybeans in MS and MT (stage R2).

Element	Trifoliate with petiole			Trifoliate without petiole		
	Low	Sufficient	High	Low	Sufficient	High
	------------------------------------ g/kg ------------------------------------					
N	< 36.8	36.8 - 46.9	> 46.9	< 50.6	50.6 - 62.4	> 62.4
P	< 2.3	2.3 - 3.4	> 3.4	< 2.8	2.8 - 3.9	> 3.9
K	< 17.3	17.3 - 25.7	> 25.7	< 14.4	14.4 - 20.3	> 20.3
Ca	< 6.8	6.8 - 11.8	> 11.8	< 6.2	6.2 - 11.6	> 11.6
Mg	< 2.9	2.9 - 4.7	> 4.7	< 3.0	3.0 - 4.9	> 4.9
S	< 2.1	2.0 - 3.0	> 3.0	< 2.4	2.4 - 3.3	> 3.3
	---------------------------------- mg/kg ----------------------------------					
B	< 33	33 - 50	> 50	< 37	37 - 56	> 56
Cu	< 6	6 - 11	> 11	< 7	7 - 12	> 12
Fe	< 59	59 - 120	> 120	< 77	77 - 155	> 155
Mn	< 28	28 - 75	> 75	< 38	38 - 97	> 97
Zn	< 31	31 - 58	> 58	< 41	41 - 78	> 78

Source: Kurihara et al. (2008).

Another underutilized application by farmers, or even consultants, is leaf analysis to confirm visual diagnoses of symptoms related to nutritional disorders or other biotic or abiotic factors. In Figure 5A, soybean leaves grown in sandy soil and under water stress are observed, showing burning at the edges caused by boron toxicity (235 mg/kg of B), due to the management of fertilization containing boron in the planting furrow. In Figure 5B, we see soybean leaves with wrinkling or curling caused by manganese toxicity (2765 mg/kg of Mn), a symptom that can be confused with soybean leaf wrinkling, a phenomenon not completely understood but common in some areas, especially in basalt soils.

In Figure 5C, the soybean leaf shows spots that could initially be attributed to some biotic causal agent or confused with nutritional disorders (Castro et al., 2022). Finally, in Figure 5D, corn leaves with potassium deficiency (6.45 g/kg of K) are observed, collected from clayey soil areas with low levels of this nutrient (0.09 $cmol_c/dm^3$), under suspicion of a high population of nematodes (Duarte et al., 2022).

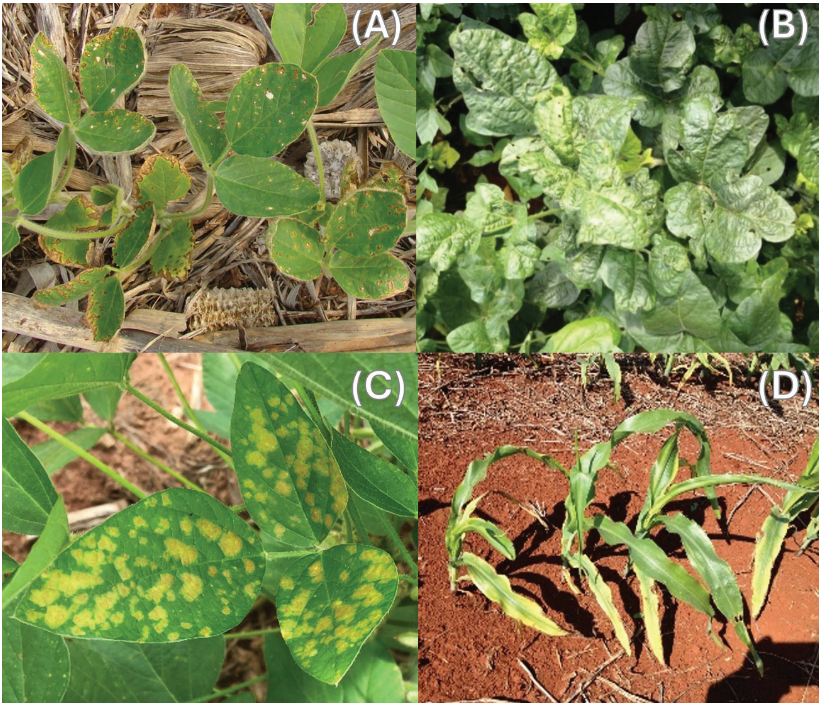

Figure 5. Plants with visual symptoms of nutritional disorders. (A) Soybean with boron toxicity; (B) Soybean with manganese toxicity; (C) Soybean with yellow leaf disorder symptoms; (D) Corn with potassium deficiency.

Soybean Fertilization

In soil fertility management, the technical criteria for fertilization recommendations is based on the nutritional requirements of plants and the crop's potential response, prioritizing the application of primary macronutrients through NPK formulations or by applying simple sources and inoculants to promote biological nitrogen fixation (BNF).

Soybean fertilization should be carried out based on technical criteria that allow for the assessment of soil fertility to enable efficient use of fertilizers, meet the nutritional needs of plants, and achieve maximum economic efficiency for the producer. To this end, chemical soil analysis and foliar diagnosis are highly effective tools.

Another possibility for evaluating fertilization is the Nutrient Use Efficiency (NUE) which is calculated based on the balance of fertilization and indicates whether management is in equilibrium, leading to a reduction or increase in nutrient levels in the soil, with possible impacts on yield and/or costs (Resende et al., 2019).

Nitrogen

Soybean obtains most of its nitrogen (N) for metabolic functions through natural biological fixation processes carried out in root nodules, which are symbiotic associations with bacteria of *Bradyrhizobium* genus — "Biological Nitrogen Fixation" (BNF). Thus, the technical recommendation for managing N in soybean cultivation is based on best practices for the correct application of inoculants with high quality containing these bacteria (Hungria; Nogueira, 2020).

There is much discussion regarding the possible benefits of using mineral N in soybeans; however, most results obtained under field conditions demonstrate that applying N at sowing (Oliveira Junior et al., 2015) or as a top-dressing via soil and/or foliar application does not increase significantly yield. Nevertheless, in cases where NPK formulations containing MAP (9%-10% N and 50%-55% P_2O_5) are used as a P source, it is advisable to avoid applying N rates greater than 20 kg/ha to ensure proper establishment of BNF.

Although the symptom of N deficiency, characterized by **chlorosis in the lower third leaves (old leaves)**, is rarely observed in soybeans grown under field conditions. In areas with low organic matter (OM) content, a history of non-inoculation of soybeans, and lack of cobalt (Co) and molybdenum (Mo) application, the occurrence of plants with slightly pale coloration (**light green**) and poor nodulation, may indicate N deficiency in the plants (Figure 6).

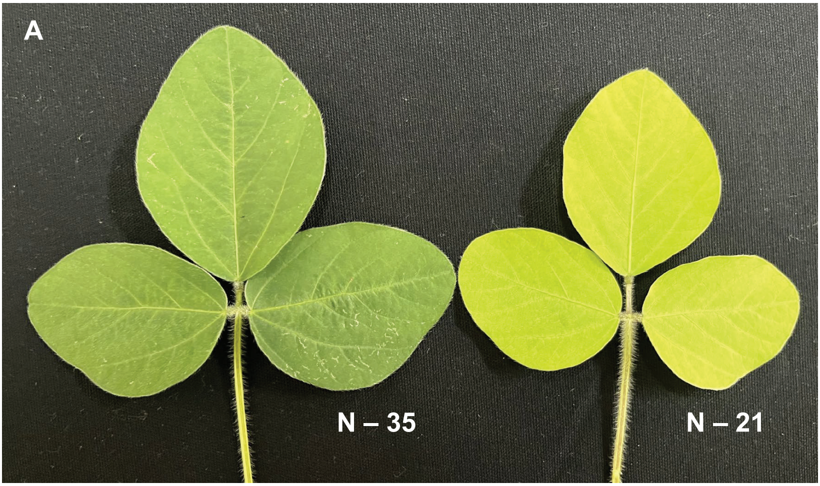

Figure 6. Soybean leaves collected from commercial fields at the R1 stage, in an area with inoculation plus cobalt and molybdenum application. Leaves without (A) and with (B) nitrogen deficiency symptoms.

Phosphorus and Potassium

Phosphorus (P) and potassium (K) are the nutrients that must receive prior attention in most soybean fertilization systems because, in addition to being deficient in tropical agricultural soils, they are, after N, the nutrients exported in the largest quantities through the grains (Table 2).

To increase or maintain soil fertility and achieve the yield potential of soybeans with technical and economic efficiency, in addition to the availability of these nutrients in the soil, the criteria for fertilization recommendations must consider the source, rate, form, and timing of fertilizer application.

Historically, soybean production areas have been fertilized with quantities of P far exceeding exports, resulting in improved average availability of this nutrient in soils, with the potential for increased efficiency in utilizing fertilizer sources through the adoption of best management pratices (Pavinato et al., 2020). On the other hand, the K fertilization balance is neutral or deficient in commercial fields across all regions of Brazil (Oliveira Junior et al., 2013; Filippi et al., 2021).

The efficiency use of fertilizers and the fertilization response are highly dependent on climatic factors and primarily on the physical, chemical, and biological properties of soils. There are regional fertilizer recomendations, based on results from scientific experimentation to determine calibration curves for response to fertilization.

Cerrado region (Sousa et al., 2016)

The indication of the quantity of nutrients is based on the results of soil analysis, sampled from the 0-20 cm layer. Table 7 presents the classes of P availability for Mehlich-1 and anion exchange resin extractants. For soybean, it is recommended to raise the P content to the lower limit of the adequate class, above the minimum levels required to achieve 80% to 90% of the potential yield, in the absence of P application during the agricultural year.

Table 7. Classes of phosphorus (P) availability, using resin and Mehlich-1 methods, for the indication of phosphate fertilization in rainfed systems with annual crops in the *Cerrados*.

P availability class	Yield potential	Resin P	Mehlich-1 P (as function of clay, %)			
			≤ 15	16 a 35	36 a 60	> 60
	%	--------------------	mg/dm³	--------------------		
Very low	0–40	0–5	0–6.0	0–5.0	0–3.0	0–2.0
Low	41–60	6–8	6.1–12.0	5.1–10.0	3.1–5.0	2.1–3.0
Medium\1	61–80	9–14	12.1–18.0	10.1–15.0	5.1–8.0	3.1–4.0
Adequate	81–90	15–20	18.1–25.0	15.1–20.0	8.1–12.0	4.1–6.0
High	91–100	21–35	25.1–40.0	20.1–35.0	12.1–18.0	6.1–9.0
Very high	100	> 35	> 40.0	> 35.0	> 18.0	> 9.0

\1 The upper limit of this class indicates the critical level. Fonte: Sousa et al. (2016)

Phosphorus fertilization:

Corrective phosphate fertilization aims to raise the availability of P in the soil to the “adequate” class (Table 7). The required rate of phosphate fertilizer for this class can be estimated by the method based on the P buffering capacity (PBC) of the soil. The PBC corresponds to the rate of P_2O_5 necessary to increase the P content by 1 mg/dm³ in the sampled top layer (0-20 cm) and varies with the soil content and the P extractant used (Table 8). Once the current P content in the soil is known, the P_2O_5 rate for corrective fertilization is calculated using the following equation

$$\text{P rate (kg/ha } P_2O_5) = (\text{Target P content} - \text{Current P content}) \times \text{PBC}$$

Table 8. Critical P levels for 80% of potential yield and Phosphorus Buffering Capacity (PBC) values to determine the phosphate fertilizer rate for corrective fertilization of annual crops in the *Cerrado* region, based on soil clay content, for the Mehlich-1 and Resin methods.

Clay content (%)	**Critical P index to 80% potential yield** (1)		**Phosphorus buffering capacity (PBC)** (2)	
	Mehlich-1	**Resin**	**Mehlich-1**	**Resin**
	--------------- mg/dm^3 --------------		**--- (kg/ha P_2O_5) / (mg/dm^3) ---**	
10–15	20	15	5	6
16–20	18	15	6	7
21–25	17	15	7	8
26–30	15	15	9	9
31–35	14	15	11	10
36–40	13	15	15	12
41–45	11	15	18	13
46–50	10	15	23	14
51–55	8	15	29	15
56–60	7	15	37	16
61–65	5	15	54	17
66–70	4	15	70	19

(1) To obtain the critical phosphorus level for 90% of potential yield, for crops with higher added value or lower climate risk, such as irrigated systems, multiply these values by 1.4.

(2) Soluble P_2O_5 rate to increase the phosphorus content in the soil by 1 mg/dm^3, based on samples from the 0-20 cm soil layer.

Tables 9 (Mehlich-1) and 10 (Resin) present the P rates (kg/ha of P_2O_5) for corrective fertilization, calculated based on clay content and PBC (Table 8), recommended to raise the availability of P to the critical level for achieving 80% of the crop's potential yield, depending on the clay content and the soil's phosphorus buffering capacity.

Table 9. Recommended P_2O_5 rates (kg/ha) for correcting the P contents in the soil (**Mehlich-1**) up to the value corresponding to 80% of the potential yield.

Clay content (%)	P content by Mehlich-1 (mg/dm^3)																			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	---------- kg/ha P_2O_5 ----------																			
10–15	95	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	**M**
16–20	102	96	90	84	78	72	66	60	54	48	42	36	30	24	18	12	6	**M**		
21–25	112	105	98	91	84	77	70	63	56	49	42	35	28	21	14	7	**M**			
26–30	126	117	108	99	90	81	72	63	54	45	36	27	18	9	**M**					
31–35	143	132	121	110	99	88	77	66	55	44	33	22	11	**M**						
36–40	180	165	150	135	120	105	90	75	60	45	30	15	**M**							
41–45	180	162	144	126	108	90	72	54	36	18	**M**									
46–50	207	184	161	138	115	92	69	46	23	**M**										
51–55	203	174	145	116	87	58	29	**M**												
56–60	222	185	148	111	74	37	**M**													
61–65	216	162	108	54	**M**															
66–70	210	140	70	**M**																

M: Maintenance rates corresponding to 15 kg of P_2O_5 and 10 kg of P_2O_5 for each expected ton of grain, respectively for soils with adequate or high phosphorus levels; Data calculated from Table 8.

Table 10. Recommended P_2O_5 rates (kg/ha) for correcting the P contents in the soil (**Resin**) up to the value corresponding to 80% of the potential yield.

Clay content (%)	P content by Resin (mg/dm^3)														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	---------- kg/ha P_2O_5 ----------														
10–15	84	78	72	66	60	54	48	42	36	30	24	18	12	6	**M**
16–20	98	91	84	77	70	63	56	49	42	35	28	21	14	7	**M**
21–25	112	104	96	88	80	72	64	56	48	40	32	24	16	8	**M**
26–30	126	117	108	99	90	81	72	63	54	45	36	27	18	9	**M**
31–35	140	130	120	110	100	90	80	70	60	50	40	30	20	10	**M**
36–40	168	156	144	132	120	108	96	84	72	60	48	36	24	12	**M**
41–45	182	169	156	143	130	117	104	91	78	65	52	39	26	13	**M**
46–50	196	182	168	154	140	126	112	98	84	70	56	42	28	14	**M**
51–55	210	195	180	165	150	135	120	105	90	75	60	45	30	15	**M**
56–60	224	208	192	176	160	144	128	112	96	80	64	48	32	16	**M**
61–65	238	221	204	187	170	153	136	119	102	85	68	51	34	17	**M**
66–70	266	247	228	209	190	171	152	133	114	95	76	57	38	19	**M**

M: Maintenance rates corresponding to 15 kg of P_2O_5 and 10 kg of P_2O_5 for each expected ton of grain, respectively for soils with adequate or high phosphorus levels; Data calculated from Table 8.

Gradual corrective fertilization: This method can be used as an alternative to full correction, generally for clayey and very clayey soils, where the required rates are high. This practice involves adding to the maintenance fertilization in the sowing row, a fraction of the amount of phosphorus defined for corrective fertilization over a period of 3 to 5 growing seasons, aiming to achieve adequate phosphorus availability (Table 10). As an example, to reach the highest corrective rate required to raise phosphorus above the critical level in a soil with more than 70% clay content (Table 12), it would be necessary to add 42 kg/ha of P_2O_5 to the sowing fertilization for 5 years.

Maintenance fertilization: Maintenance fertilization is recommended when phosphorus availability is adequate or high, and the rates must be sufficient to maintain the yield potential of the areas. In these cases, the fertilization recommendation, in a well-managed no-till system without chemical, physical, or biological limitations, is to apply rates corresponding to 15 kg of P_2O_5 and 10 kg of P_2O_5 for each expected ton of grain, respectively for soils with phosphorus levels in the adequate or high phosphorus availability classes (Table 10). For soils in the very high class, phosphorus fertilization may be suspended for one or more years, until the level returns to the high class.

Potassium fertilization (Vilela et al., 2004):

For soils in the *Cerrado* region, two systems are adopted to correct K deficiency. Total corrective fertilization, where K rates are applied to correct the deficiency, followed by annual applications to restore the K removed by the crops, or gradual corrective fertilization, which consists of annually applying K rates higher than the crop's requirements to gradually increase the nutrient availability in the soil until reaching the critical level.

The fertilization recommendation is subdivided into two CEC classes: soils with CEC at pH 7.0 less than 4.0 cmolc/dm³ and soils with CEC at pH 7.0 greater than or equal to 4.0 cmolc/dm³ (Table 11). In soils with CEC less than 4.0 cmolc/dm³, the potential for K leaching losses is high. In this case, splitting rates greater than 40 kg/ha of K_2O or broadcasting the application is recommended. Rates of K above 100 kg/ha of K_2O, regardless of the soil's CEC, should preferably be split or broadcast.

Table 11. Interpretation of soil analysis and recommendation of corrective K fertilization for annual crops based on nutrient availability in *Cerrado* soils.

K availability		Interpretation	Total correction[1]	Gradual correction
mg/kg	$cmol_c/dm^3$		--------- kg/ha of K_2O ---------	
CEC at pH 7.0 < 4.0 $cmol_c/dm^3$				
< 16	< 0.04	Low	50	70
16 to 30	0.04 - 0.08	Medium	25	60
31 to 40	0.08 - 0.10	Adequate[2]	0	0
> 40	> 0.10	High[3]	0	0
CEC at pH 7.0 ≥ 4.0 $cmol_c/dm^3$				
< 25	< 0.06	Low	100	80
25 to 50	0.06 - 0.13	Medium	50	60
51 to 80	0.13 - 0.20	Adequate[2]	0	0
> 80	> 0.20	High[3]	0	0

[1] Total corrective fertilization must be complemented with maintenance fertilization in the planting row. [2] For soils with K levels within this range, maintenance fertilization is recommended according to the expected yield. [3] For soils with K levels within this range, 50% of the maintenance fertilization or the expected or estimated K extraction based on the last harvest is recommended.

If the K level is adequate, to avoid a decrease in contents, it is recommended to apply maintenance fertilization annually, which corresponds to 20 kg of K_2O for each ton of grain (soybean) expected to be produced. For soils with high K levels, until adequate levels are reached, maintenance fertilization equivalent to 50% of K removed may eventually be adopted.

Mato Grosso State

The technical recommendations for the state of Mato Grosso were compiled from the Research Bulletin - 2019/2020 (Zancanaro et al., 2019). Tables 12 to 15 serve as a reference for interpreting soil analyses and as suggestions for fertilization, considering the research results from the Fertilization Monitoring Program of Fundação MT.

Phosphorus fertilization:

Phosphorus is the nutrient that most limits productivity in soils of the *Cerrado* region. However, there are many areas that have been cultivated for several years and/or have received significant investment in fertilization that currently exhibit adequate or high levels of P.

In general, phosphorus is also the nutrient with the highest cost in soybean fertilization in the state of Mato Grosso, and it significantly impacts operational aspects. Differences in cultivation history (investment history and phosphorus levels in the soil) are key determinants of the fertilization strategy to be adopted. Tables 12 to 13 can serve as a reference for interpreting soil analysis results and as suggestions for fertilization.

Table 12. Interpretation of soil analyses from samples collected at a depth of 0-20 cm for phosphorus fertilization recommendations (Mehlich-1).

Clay content	Phosphorus availability class (M-1)			
	Very low	Low	Medium	Adequate
------- % -------	---------------------------- *mg/dm³* ----------------------------			
61 - 80	< 2.0	2.0 to 3.9	4.0 to 6.0	> 6.0
41 - 60	< 5.0	5.0 to 7.9	8.0 to 12.0	> 12.0
21 - 40	< 6.0	6.0 to 11.9	12.0 to 18.0	> 18.0
≤ 20	<8.0	8.0 to 14.9	15.0 to 20.0	> 20.0

Note: When interpreting the results of soil analyses from samples collected in fields with a history of fertilization with natural phosphates or less soluble phosphate fertilizers, it is important to consider that the Mehlich-1 method tends to overestimate the available phosphorus levels in the soil. In this case, the recommended analysis method is the resin method.

Table 13. Recommendation for corrective broadcast[1] phosphorus fertilization according to soil clay and phosphorus availability class (Mehlich-1).

Clay content	Phosphorus availability class (M-1)	
	Very low	Low
------- % -------	------------------ *kg/ha of P_2O_5*[2] ------------------	
61 - 80	300	200
41 - 60	250	175
21 - 40	200	135
≤ 20	150	100

[1] The corrective phosphorus fertilization should be evaluated based on the amount of phosphorus, considering the clay content, the market value of soybeans, and the expected return from the higher productivity that can be achieved in the first four years. [2] The suggested quantities of phosphorus refer to soluble phosphorus (CNA + Water).

In Table 14, the suggested phosphorus quantities refer to a productivity expectation of 60 sc/ha (3,600 kg/ha) for areas with several years of cultivation and 55 sc/ha (3,300 kg/ha) for new areas. Achieving higher productivity also depends on the uniformity of the crop, as new areas generally exhibit greater variability.

Table 14. Recommendation for maintenance phosphorus fertilization applied in the furrow according to the availability of phosphorus in *Cerrado* soils for Mato Grosso state.

Clay content	Phosphorus content class – Mehlich-1			
	Very low	Low	Medium	Adequate
------- % -------	------------------------ kg/ha of P_2O_5[1]	------------------------		
61 - 80	≥ 120[2]	110	90	60[3]
41 - 60	≥ 120	100	80	60
21 - 40	120	100	80	60
≤ 20	120	90	80	60

[1] The suggested quantities of phosphorus refer to soluble phosphorus, in Neutral Ammonium Citrate (NAC) + Water, and may vary based on the desired productivity level, investment level, and expected price for soybeans. [2] Research by the Fundação MT Fertilization Monitoring Program has found positive and linear responses to phosphorus applied in the planting row up to the highest quantity applied (132 kg/ha of P_2O_5) when soybeans are sown under conditions where soil phosphorus levels are very low. Therefore, if phosphorus in the soil is classified as low or very low and there is an opportunity to invest more in phosphorus and/or soybean prices are promising, larger quantities than those suggested in the table may be used. [3] The recommended quantities when the phosphorus level is interpreted as adequate correspond to a maintenance strategy for the mentioned yield levels. For productivity levels greater than those mentioned above, the recommended quantity of phosphorus for the fertilization and replenishment strategy is proportional to the productivity achieved or desired.

The decision to apply fertilizer in the seed row or as a broadcast depends on the area diagnosis, the farm objectives, and operational management. However, one strategy is to alternate the method of application of phosphate fertilizer during the years or harvests.

Potassium fertilization:

In Table 15, the interpretation of soil analysis results and the recommendation for potassium fertilization for soybean cultivation are presented, based on research results from Fundação MT.

Table 15. Interpretation of potassium levels in the soil and recommendation for fertilization (kg/ha of K_2O) for the expected yields of 3600 kg/ha (60 sacks/ha).

Levels	K availability content		K rate
	------ mg/dm^3 ------	----cmol$_c$/dm^3----	-- kg/ha de K_2O --
Adequate	> 60	> 0.15	72 a 80[\1]
Medium	40 a 60	0.10 a 0.15	80 a 100
Low	20 a 40	0.05 a 0.10	100 a 120
Very low	< 20	< 0.05	120 a 140

[\1] The recommended quantities correspond to the replacement of the expected extraction (20 kg/ha to 23 kg/ha of K_2O for every 1000 kg of grains).

The results from Fundação MT have shown that in very sandy soils, there is no response to fertilizations greater than 120 kg/ha of K_2O, both in terms of yield and K levels in the soil. In other words, in sandy soils, farmers should rarely work with low K quantities (less than the amounts exported) and should also avoid very high fertilizations (120 kg/ha to 140 kg/ha). In this case, rather than investing in higher quantities of K, it is more important to invest in the timing of its application and, above all, in crops with high nutrient recycling capacity, such as millet or *brachiaria*, for example.

It is advisable to avoid applying quantities above 50 kg/ha of K_2O in the seed furrow. In soils with less than 40% clay, potassium fertilization should be done with one-third of the rate in the seed row and two-thirds as a top-dressing, which should be applied 30 to 40 days after plant emergence, for both early and late cycle cultivars. Special care should be taken with the uniformity of application in broadcast applications, considering the equipment and, primarily, the reach of the application.

Minas Gerais State

Table 16 presents the classes of interpretation for phosphorus availability according to soil clay content or the value of residual P, as well as for K. Based on the interpretation classes for the availability of these nutrients in the soil, the recommended rates of P and K are provided in Table 17.

Table 16. Interpretation classes for phosphorus availability according to soil clay content or remaining phosphorus value (P-rem), as well as for potassium.

Reference attributes	Content class				
	Very low	Low	Medium\3	High	Very high
Clay (%)	-------------- Available phosphorus\1 (mg/dm^3) --------------				
>60	≤ 2.7	2.8 - 5.4	5.5 - 8.0	8.1 - 12.0	>12.0
35 a 60	≤ 4.0	4.1 - 8.0	8.1 - 12.0	12.1 - 18.0	>18.0
15 a 35	≤ 6.6	6.7 - 12.0	12.1 - 20.0	20.1 - 30.0	>30.0
<15	≤10.0	10.1 - 20.0	20.1 - 30.0	30.1 - 45.0	>45.0
P-rem\2 (mg/L)					
0 – 4	≤ 3.0	3.1 - 4.3	4.4 - 6.0	6.1 - 9.0	>9.0
4 - 10	≤ 4.0	4.1 - 6.0	6.1 - 8.3	8.4 - 12.5	>12.5
10 - 19	≤ 6.0	6.1 - 8.3	8.4 - 11.4	11.5 - 17.5	>17.5
19 - 30	≤ 8.0	8.1 - 11.4	11.5 - 15.8	15.9 - 24.0	>24.0
30 - 44	≤11.0	11.1 - 15.8	15.9 - 21.8	21.9 - 33.0	>33.0
44 - 60	≤15.0	15.1 - 21.8	21.9 - 300	30.1 - 45.0	>45.0
	-------------- Available potassium\1 --------------				
$cmol_c/dm^3$	<0.04	0.04 - 0.10	0.11 - 0.18	0.18 - 0.31	> 0.31
mg/dm^3	≤ 15	16 a 40	41 a 70	71 a 120	> 120

\1 Mehlich-1 method. \2 P-rem = the concentration of phosphorus in the equilibrium solution after stirring the soil-solution mixture with a 10 mmol/L $CaCl_2$ solution containing 60 mg/L of phosphorus in a 1:10 ratio for 1 hour. \3 The upper limit of this class indicates the critical index. Source: Alvarez V. et al. (1999).

Table 17. Fertilization with P and K for a yield of 3000 kg of grains.

Phosphorus availability			Potassium availability		
Low	Medium	High	Low	Medium	High
---------- kg/ha of P_2O_5 ----------			---------- kg/ha of K_2O[1] ----------		
120	80	40	120	80	40

[1] Do not apply more than 50 kg/ha in the furrow. Source: Alvarez V. et al. (1999).

São Paulo State (Quaggio et al., 2022):

In soils with up to 6.0 mg/dm³ of phosphorus (extracted by anionic resin), it is recommended to apply 100 kg/ha of P_2O_5, incorporated into the soil, in addition to the recommended rates for sowing fertilization (Table 18).

It is advisable to avoid applying more than 50 kg/ha of K_2O to prevent stand reduction due to saline stress. Higher rates should be split, with application as a top dressing 20 to 25 days after germination. In clayey soils with low K levels, when the recommended rates are equal to or greater than 80 kg/ha of K_2O, the top dressing should be advanced to the pre-sowing phase and broadcasted.

Table 18. Mineral fertilization at planting for the state of São Paulo.

Expected yield	P-resin (mg/dm^{-3})			Exchangeable K^+ ($mmol_c/dm^3$)		
	0–15	16–40	>40	0–1.5	1.6–3.0	>3.0
---- *t/ha* ----	------ P_2O_5 (kg/ha)------			------K_2O (kg/ha)------		
< 3.0	120	80	30	100	60	40
3.0 – 4.0	140	100	40	120	80	60
4.0 – 5.0	160	120	60	140	100	80
> 5.0	*	140	80	160	120	100

* Achieving these yield levels with localized phosphorus application is difficult in soils with low P content.

In soils with more than 80 mg/dm³ of P (resin), apply only 20 kg/ha of P_2O_5 in the planting furrow as starter fertilization. For soils with very high K levels, above 6.0 $mmol_c/dm^3$, potassium fertilization is not recommended.

Paraná State

Phosphorus and potassium rates vary according to the nutrient content classes in soils (Tables 19 and 20) and should preferably be applied locally in the planting row.

For K fertilization specifically, in soils with more than 35% clay and adequate K availability, broadcast application may be done up to 30 days before planting. In localized application within the planting furrow, the fertilizer quantity should be limited to rates below 60 kg/ha of K_2O due to potential saline effects that can harm seed germination and early seedling development (Figure 7), especially in sandy soils. This symptom can be mistaken for other factors, including K deficiency. To enhance fertilization efficiency and achieve the total K requirement, additional potassium may be applied in broadcast over the total area until the plants reach the V4/V5 vegetative stages.

Figure 7. Soybean seedling showing salinity symptoms at V2 stage, grown in soil with electrical conductivity (EC) of 0.72 ds/m, pH ($CaCl_2$) of 6.95, and K content of 1.20 $cmol_c/dm^3$.

Table 19. Phosphorus fertilization recommendation (kg/ha of P_2O_5) for soybean in Paraná state.

Class	P content[1]	P_2O_5 rate	P content[1]	P_2O_5 rate	P content[1]	P_2O_5 rate	P content[1]	P_2O_5 rate
	mg/dm^3	kg/ha	mg/dm^3	kg/ha	mg/dm^3	kg/ha	mg/dm^3	kg/ha
CEC (cmol$_c$/dm^3)	-------- < 4 ---------		-------- 4 - 8 --------		-------- 8 - 12 --------		-------- 12 - 16 --------	
Very low	< 6.0	130	< 5.0	150	< 4.0	160	< 3.0	180
Low	6.0–14.0	100	5.0–10.0	120	4.0–8.0	130	3.0–5.0	150
Medium[2]	14.1–**20.0**	80	10.1–**16.0**	90	8.1–**12.0**	100	5.1–**8.0**	110
High[3,5]	20.1–40.0	M	16.1–32.0	M	12.1–18.0	M	8.1–15.0	M
Very high[4,5]	> 40.0	R	> 32.0	R	> 18.0	R	> 15.0	R

[1] Labile P extracted by Mehlich-1. [2] The upper limit of this class indicates the critical index. [3] The maintenance rate (M), based on fertilization balance, represents a 75% replacement efficiency (R) of the nutrient quantity exported (11 kg P_2O_5 per ton of grain). [4] The replacement rate (R), based on fertilization balance, corresponds to a 100% replacement efficiency of the nutrient quantity exported (11 kg P_2O_5 per ton of grain). In this class, the rate can be reduced proportionally or even omitted, with periodic soil analysis monitoring required. [5] System-based fertilization practices can be applied in areas with available P levels in the high and very high classes. Source: Embrapa Soja (2024).

Table 20. Potassium fertilization recommendation (kg/ha of K_2O) for soybean in Paraná state.

Class	K content[\1]	K_2O rate	K content[\1]	K_2O rate	K content[\1]	K_2O rate	K content[\1]	K_2O rate
	$cmol_c/dm^3$	kg/ha	$cmol_c/dm^3$	kg/ha	$cmol_c/dm^3$	kg/ha	$cmol_c/dm^3$	kg/ha
CEC ($cmol_c/dm^3$)	-------- < 4--------		--------4 - 8--------		--------8 - 12--------		--------12 - 16--------	
Very low	< 0.04	140	< 0.06	180	< 0.09	220	< 0.13	240
Low	0.04–0.08	120	0.07–0.11	160	0.10–0.18	180	0.13–0.26	200
Medium[\2]	0.09–**0.12**	90	0.12–**0.22**	130	0.19–**0.32**	150	0.27–**0.41**	160
High[\3,5]	0.13–0.24	M	0.23–0.44	M	0.33–0.64	M	0.42–0.82	M
Very high[\4,5]	> 0.24	R	> 0.44	R	> 0.64	R	> 0.82	R

[\1] Exchangeable K extracted by Mehlich-1. [\2] The upper limit of this class indicates the critical index. [\3] The maintenance rate (M), based on fertilization balance, corresponds to a 90% replacement efficiency (R) of the nutrient quantity exported (22 kg K_2O per ton of grain). [\4] The replacement rate (R), based on fertilization balance, represents a 100% replacement efficiency of the nutrient quantity exported (22 kg K_2O per ton of grain). In this class, the rate may be proportionally reduced or omitted entirely, with ongoing monitoring through periodic soil analysis required. [\5] System-based fertilization practices can be applied in areas with available K levels in the high and very high classes. Source: Embrapa Soja (2024).

Time and methods of fertilizer application

The decision-making process regarding the method of P and/or K fertilization, whether applied in the sowing row or broadcast on the soil surface, depends on various factors. Although agronomic considerations are the primary ones, logistics, often linked to the need for greater efficiency in management operations, frequently dictate the method of application, especially in large areas.

However, it is well known that P is a nutrient with low mobility and tends to concentrate in the surface layers of the soil, with a sharp decrease in availability as soil depth increases (Bataglia et al., 2009; Zancanaro et al., 2019; Oliveira Junior et al., 2019). Figure 8 represents the characteristic distribution of P in tropical Oxisols. Similarly, the distribution of P by depth in the sedimentary soils of Mato Grosso follows the same trend (Figure 9).

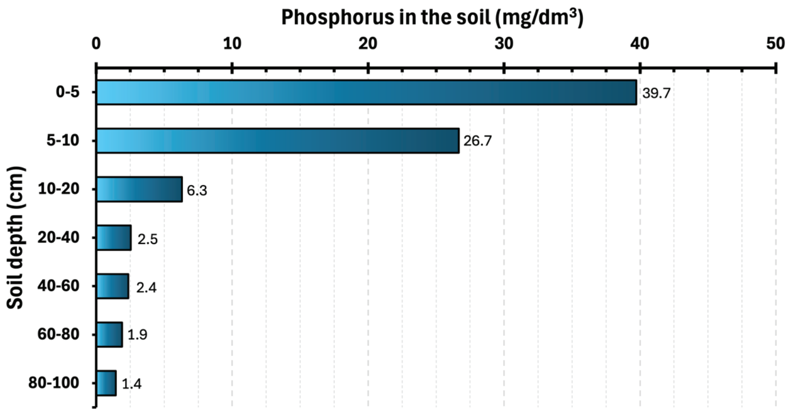

Figure 8. Distribution of phosphorus along the soil profile, from 0 to 100 cm depth. Source: Oliveira Junior et al. (data not published)

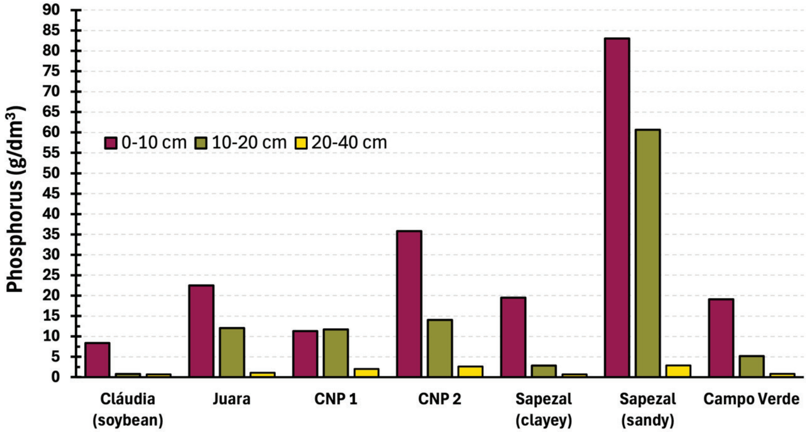

Figure 9. Distribution of phosphorus along the soil profile, from 0 to 40 cm depth, in farms from Mato Grosso state, Brazil.

The best method of applying phosphate fertilizer is localized in the furrow, close to the roots, since the primary process of nutrient-soil contact with the roots is diffusion. However, particularly in areas with high P availability and low risk of water deficit, it is possible to broadcast it on the soil surface, and this method can show agronomic efficiency comparable to row application (Oliveira Junior et al., 2019). The continuation of this practice, however, depends on monitoring P levels (soil fertility) in the 0-10 cm and 10-20 cm soil layers.

Potassium, available in the soil's exchangeable fraction, is more mobile than phosphorus. The processes of mass flow and diffusion determine the contact of the ion with the roots, allowing for greater flexibility regarding the timing and method of application, facilitating logistics and fertilizer management. Generally, K can be applied locally in the planting row, respecting the maximum limits indicated for each region. Alternatively, in soils with established fertility, K can be applied before planting or as a top-dressing until the V4/V5 stage of soybean development (Figure 10).

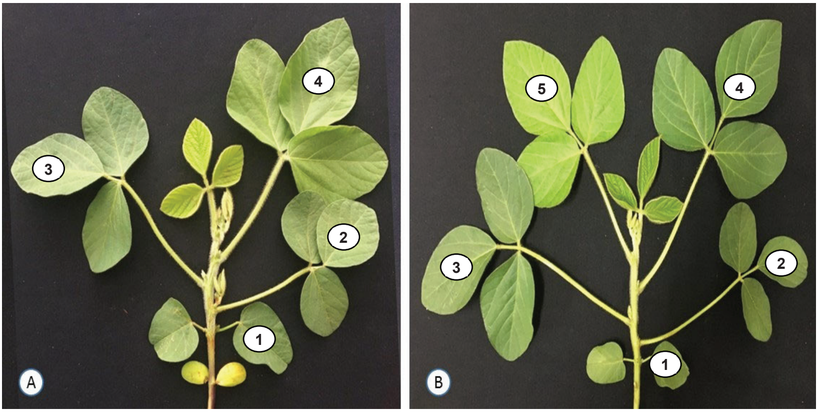

Figure 10. Soybean plants at V4 (A) and V5 (B) phenological stages.

Tables 19 and 20 present the critical indexes of P and K in the soil and the sufficiency ranges required to achieve high soybean yields in the state of Paraná, Brazil. This set of information is essential for determining fertilizer recommendations, allowing, with confidence, even the reduction of rates or the absence of fertilization under certain conditions. Another management option is the anticipation of soybean fertilization during the winter crop (Foloni et al., 2018). However, for the adoption of these alternatives, careful soil fertility monitoring is crucial to prevent nutrient levels from falling below the critical threshold. In addition to soil analysis, it is important to evaluate the nutrient input-output balance, crop yields within the production system, and leaf analysis.

Fertilizer sources

For P and K, the nutrient concentration in the sources is an important issue, as the logistics and management of fertilizer application can be significantly affected depending on the sources chosen.

For P, some manufacturers have recommended reducing rates of alternative or special sources, claiming higher efficiency compared to soluble mineral sources. This stance has been common for organomineral fertilizers. However, both soluble mineral sources, reactive P, and organomineral sources generally exhibit a minimum agronomic efficiency of 75% when applied under conditions of high or very high fertility. Thus, the recommended rate of any P source should be based on the soluble P_2O_5 content, in neutral ammonium citrate (NAC) + water and/ or 2% citric acid.

For potassium, the main source is potassium chloride, which offers the greatest economic viability and transportation cost efficiency. However, multi-nutrient sources have been made available to producers, and in these cases, the recommended quantity to be applied should be based on the soluble K content in NAC + Water or 2% citric acid.

As a basic economic rule, the decision to purchase fertilizer sources should consider the total cost of product delivery per unit of soluble nutrient (Purchase Factor – PF), resulting in the lowest cost/benefit ratio.

$$Purchase\ Factor\ (\boldsymbol{PF}) = \frac{(FertP + SP)}{\%Nutr}$$

where:

FertP = Fertilizer price (R$);

SP = Shipping Price (R$/km x distance in km);

%Nutr = Soluble nutrient concentration in NAC+water or 2% citric acid.

Visual diagnosis of phosphorus and potassium deficiency

Unlike many nutrients, phosphorus deficiency in soybeans does not manifest through significant changes in leaf color, shape, or leaf texture, making its identification or even suspicion difficult. However, in field conditions, the plants exhibit slower growth, becoming smaller than those grown in soils with adequate P levels. When the smaller size of the plants occurs uniformly across the field, it may go unnoticed, or when it occurs in patches, it can be mistaken for issues like soil compaction, nematodes, or other biotic and/or abiotic causes

Experiments conducted since the 1980s with 12 combinations of available P and K levels in an Oxisol in Londrina, Brazil, demonstrate this reduced plant size (Figure 11), which consequently leads to fewer pods and grains. As the soil P levels decreased from 11 mg/dm³ to 7 mg/dm³, and then 3 mg/dm³, P absorption and accumulation in the leaves dropped from 3.9, 2.6 and 2.1 g/kg, limiting the number of pods per plant, which decreased from 56 to 33 and then 10, respectively.

In Figure 11D, it is possible to visualize an area in its first soybean crop, following the conversion of a degraded pasture into a grain production area, located in Torixoréu, Mato Grosso state, Brazil. In this area, P deficiency was identified prior to the introduction of soybeans; however, two sowing lines became clogged during a section, interrupting the distribution of phosphate fertilizer and highlighting a severe P deficiency in the plants. The plants showed reduced initial growth and reached a smaller final size. This soybean field was planted in an Oxisol with 480 g/kg of clay and a low resin-P level (~5.7 mg/dm³), high adsorption capacity indicated by a remaining phosphorus (P-rem) value of 10.7 mg/dm³.

For K, the symptoms are much more evident, with chlorosis at the leaf margins that progresses to necrosis, starting from the first trifoliate leaves but especially in the leaves and pods during the reproductive stage and until the end of the cycle, when nutrient translocation occurs. In the field, the distribution of symptoms is associated with fertilization management practices, with generalized occurrence in uniform areas that received insufficient K application. However, it is more common to observe symptoms in patches where poor surface broadcasting of the fertilizer occurred. In these areas, “hidden hunger” is often diagnosed through foliar analysis, revealing potassium deficiency in asymptomatic areas and a reduction in crop yield.

Figure 11. Soybean plants harvested from experimental plots with low (A), medium (B), and adequate (C) phosphorus levels, in Londrina-PR, and a soybean field with a failure in phosphorus fertilization in the planting row, in Torixoréu-MT (D).

An example of inadequate fertilization management was recorded in Paraná, in a field showing visual symptoms of severe K deficiency, confirmed by a very low soil K level of only 0.06 $cmol_c/dm^3$ (Figure 12A). Necrotic spots on pods were also observed (Figure 12D), commonly associated with K deficiency. However, this severe symptom of K deficiency is more frequently seen in soils with very low available K levels. In an experimental area with very clayey Oxisol, the appearance of necrosis symptoms on pods was identified only when K levels in the soil was below 0.08 $cmolc/dm^3$ and in the leaves below 11 g/kg. However, in the early stages of reduced K availability, leaf symptoms occur starting in the reproductive period, predominantly in the upper third leaves, as observed in Figures 12B and 12C.

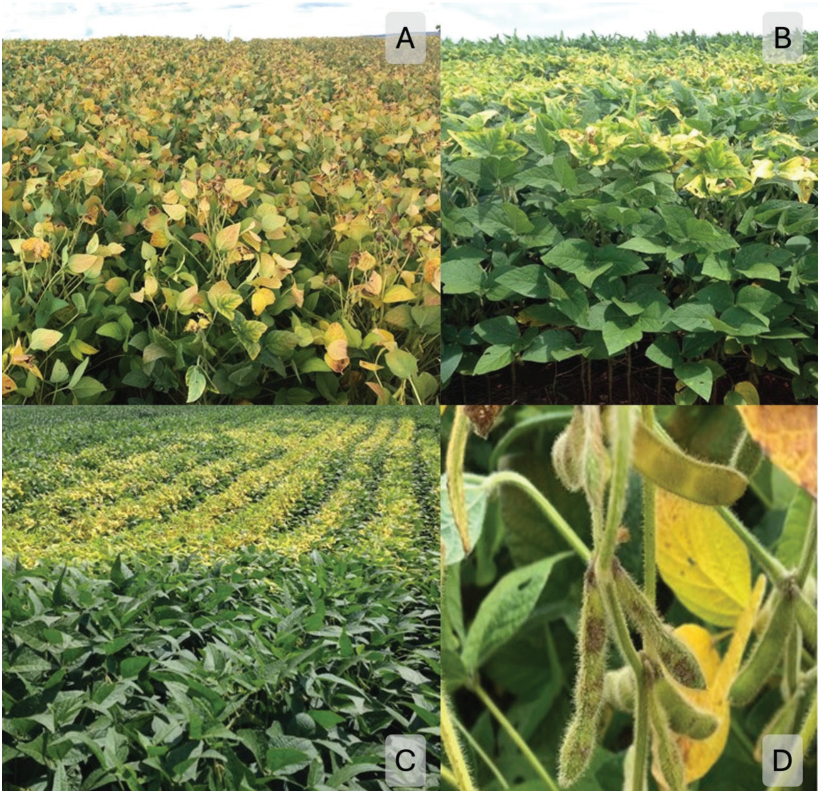

Figure 12. Soybean crop in Paraná with severe K deficiency (A); experimental plot with potassium deficiency symptoms in the upper third leaves (B and C); pod necrosis symptom (D).

Magnesium

For phosphorus (P) and potassium (K), the fertilization management criteria take into account the nutritional requirements of the plants and their potential response, leading to applications across all crops within the production systems and throughout all growing seasons. For Mg, however, the main criterion for fertilization management is not the nutritional requirement of the plants, but indirectly the need for liming. This is justified because the primary source of this nutrient is dolomitic limestone, whose main use is as an acidity corrective, with the secondary effect of increasing cations saturation through the supply of Ca^{2+} and Mg^{2+}.

Magnesium deficiency often occurs in acidic and sandy soils, where the parent material is poor in Mg (Arnold, 1967; Havlin et al., 2005), and most of the time, with medium to high K availability. In Brazil, the primary factors contributing to magnesium (Mg) deficiency in the soil include inadequate liming, excessive gypsum application (Caires, 2011), and poor fertilization management (Castro et al., 2022). For example, repeated and high applications of calcitic limestone (less than 6% of MgO), agricultural gypsum, and potassium fertilizers can induce an imbalance in soil Mg, leading to a deficiency of this nutrient.

Magnesium is a mobile nutrient in plants, so deficiency symptoms typically appear in the lower leaves. However, in crops under severe deficiency conditions, symptoms can occur throughout the entire plant, with a gradient from the younger leaves to the older ones (Figure 13). The visual symptoms of Mg nutritional deficiency in this field were due to the severe imbalance between the nutrients K (18 g/kg), Ca (11 g/kg), and Mg (0.7 g/kg), respectively.

Figure 13. Soybean field in Wenceslau Braz-PR with widespread Mg deficiency (A) and a highlighted leaf showing Mg deficiency (B).

Figure 14 illustrates soybean plants grown in sandy soil exhibiting symptoms of generalized Mg deficiency, with a gradient of severity on the lower leaves due to improper fertilization and liming management. In this area, excessive application of calcitic limestone, combined with the naturally low Mg levels in the sandstone-derived soil, likely intensified the symptoms. Additionally, the absence of Mg-containing fertilizers or the continued use of formulations with little or no Mg (Castro et al., 2020) has exacerbated the issue. By the time visible symptoms appear, yield losses due to hidden hunger have already occurred over multiple seasons and crops.

At the time of sampling, the plants were at an advanced stage of development, beyond R2 (Fehr & Caviness, 1977), a large amount of analysed leaves from this area revealed an average Mg content of 0.44 g/kg, classified as very low regardless of the plant's growth stage. The average S content was 1.7 g/kg, also considered low for soybeans. Conversely, the Mn content reached 210.8 mg/kg, an unusually high level, especially for soybeans grown in the sandy soils of the Cerrado, which naturally have lower Mn concentrations. This nutritional imbalance may be attributed to foliar Mn applications throughout the crop cycle in an attempt to mitigate a problem originally caused by Mg deficiency.

Figure 14. Soybean field showing generalized Mg deficiency on the lower leaves (Tabaporã/MT).

Sulfur

Sulfur is an important nutrient in plant metabolism, as it is a constituent of essential amino acids (cystine, cysteine, methionine), but its fertilization management has often been neglected or incorrectly applied, potentially leading to nutritional deficiency. Sulfur has low mobility in the phloem, which is why deficiency symptoms appear in the **new leaves** and are characterized by uniform chlorosis in the upper third leaves of the plants.

In the field, the symptoms of S deficiency occur broadly, making identification difficult. Mild nutritional imbalances, which characterize hidden hunger, are more common than visible symptoms. For this reason, leaf analysis is very useful for diagnosing S deficiency. In Figure 15, there are photos of soybean leaves without and with S deficiency due to low soil S levels, obtained in an experimental area with limestone and gypsum rates in Londrina-PR, Brazil. The dark green soybean leaf (A) had 3.6 g/kg of S, while the leaf with chlorosis and slightly thinning (B) had 2.0 g/kg of S.

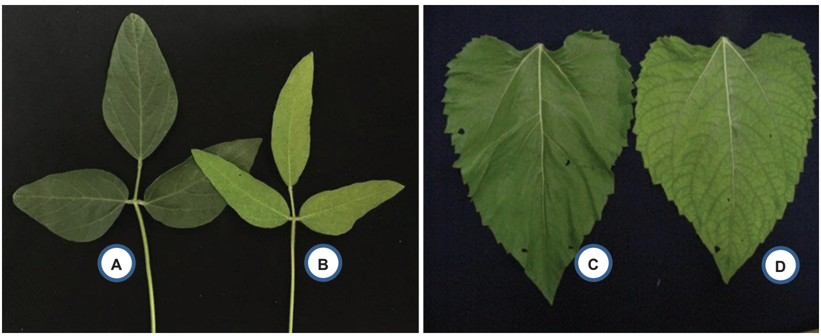

Figure 15. Soybean and sunflower leaves without and with sulfur symptoms of deficiency (chlorosis).

In areas with low S availability, crops grown in succession to soybeans may also show symptoms of nutrient deficiency. Crops subjected to high N rates may express S deficiency symptoms more intensely. In Figure 15, this effect on S absorption is observed in sunflowers cultivated in Chapadão do Céu-GO, Brazil. The darker-colored leaves (C) had 5.3 g/kg of S, while the light green leaves (D) had 2.8 g/kg of S, a value considered low for the crop (Castro & Oliveira, 2005).

Soybean plants cultivated in sandy soils frequently exhibit a light green coloration. Figure 16A shows that plants cultivated without gypsum or sulfur (S)-containing fertilizers display light green leaves that tend towards yellow. In contrast, plants grown in the same soil type but with the application of 45 kg/ha of S in the form of single superphosphate demonstrate a more vibrant green coloration (Figure 16B). The intensity of leaf greenness was measured using the SPAD index, revealing that the light green leaves had an average SPAD index of 30.1, while the darker green leaves reached an average index of 44.4. In both cases, S fertilization was the sole variable in nutrient management.

Further analysis of the leaves showed that the plants with light green leaves not only had low S levels (0.96 g/kg) but also low magnesium (Mg) levels (2.70 g/kg). These findings indicate a combined deficiency of S and Mg, underscoring the need for more effective nutrient management. Conversely, the plants with darker green leaves exhibited higher S and Mg levels, at 2.0 g/kg and 4.33 g/kg, respectively. Therefore, even in visually healthy plants with greener leaves, a hidden S deficiency was identified, reinforcing the importance of proper sulfur fertilization management.

Figure 16. Soybean plants and leaves collected from an area with (A) and without (B) symptoms of sulfur deficiency. CTECNO Campo Novo do Parecis, MT.

Gypsum is one of the main S sources used. Despite the effectiveness of this input for managing soil profile conditions, it is important to pay attention to the quantities applied. High rates of gypsum, especially in soils with a high calcium/magnesium and potassium/magnesium ratio, can induce or intensify Mg deficiency. This is observed in Figure 17, a soybean field in Chapadão do Sul-MS, Brazil, cultivated in an area with low Mg levels, a Ca/Mg ratio higher than 4, and managed with 3 tons/ha of gypsum.

Figure 17. Soybean leaf with symptoms of magnesium deficiency (1.0 g/kg of Mg) on the lower leaves due to the application of a high gypsum rate.

Unlike P, which is almost immobile in the soil and concentrates in the top few centimeters of the fertilized layer, the predominant form of mineral S in the soil is the sulfate anion (SO_4^{2-}). This anion remains in the soil solution and moves more easily through the profile, accumulating in the subsurface layers (Figure 18). Therefore, to assess the availability of this nutrient in the soil and the need for fertilization, soil analysis should be interpreted based on samples collected at two layers: 0–20 cm and 20–40 cm (Table 21)

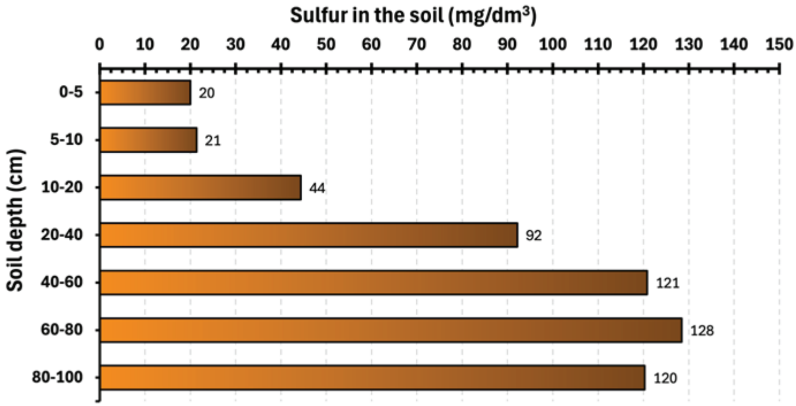

Figure 18. Characteristic distribution of sulfur in the soil profile down to 100 cm depth.

In addition to corrective fertilization, sulfur maintenance fertilization considers the full replacement of the nutrient removals, which is ~3.0 kg of S per ton of grain (Table 21).

Table 21. Recommendation of sulfur (S) correction and maintenance fertilization for soybean crops in Brazil, based on sulfur availability classes in two soil layers.

Sulfur availability in soil[1]								Sulfur Rate
CEC ≤ 5 $cmol_c/dm^3$				CEC > 5 $cmol_c/dm^3$				
------ soil layer (cm) ------				------ soil layer (cm) ------				
---- 0 a 20 ----		---- 20 a 40 ----		---- 0 a 20 ----		---- 20 a 40 ----		
------------ *mg/dm³* ------------				------------ *mg/dm³* ------------				-- *kg/ha* --
Low	<2	Low	<6	Low	<5	Low	<20	30+M[2]
	<2	Medium	6 - 9		<5	Medium	20 - 35	20+M
	<2	High	>9		<5	High	>35	10+M
Medium	2 - 3	Low	<6	Medium	5 - 10	Low	<20	20+M
	2 - 3	Medium	6 - 9		5 - 10	Medium	20 - 35	10+M
	2 - 3	High	>9		5 - 10	High	>35	M
High	>3	Low	<6	High	>10	Low	<20	10+M
	>3	Medium	6 - 9		>10	Medium	20 - 35	M
	>3	High	>9		>10	High	>35	M

[1] Methods: Extraction - $Ca(H_2PO_4)_2$ 0.01 M L^{-1}; Determination - Turbidimetry. [2] M = Maintenance: 3 kg/ha of $S\text{-}SO_4^{2-}$ for every 1,000 kg/ha of expected grain yield. Source: Modified from Sfredo et al. (2003).

The main S sources available in the market are gypsum (15% S), elemental sulfur (98% S), single superphosphate (12% S), polysulfates, as well as NPK formulations containing $S\text{-}SO_4^{2-}$, elemental S, or a combination of these sources. However, elemental sulfur must undergo an oxidation process to sulfate to become available to plants. For this reason, it is considered a slow-release source with residual effects but should be applied at least 90 days in advance.

Sulfur fertilization in Cerrado region

According to Rein and Souza (2004), if gypsum was not applied in the area and the soil is deficient in S (Table 22), 20 kg/ha of S should be applied per crop for yields of up to 3 t/ha, and 30 kg/ha of S for yields between 3 t/ha and 5 t/ha. When S availability is moderate, 15 kg/ha of S is recommended, and in areas with high sulfur availability, the nutrient does not need to be applied, except when the sulfur content in the 0-20 cm soil layer is ≤ 4 mg/dm³. In this case, it is recommended to apply 5 kg/ha of S, in sulfate form, in the planting row.

Research results in *Cerrado* areas of the State of Mato Grosso also show no response to sulfur applied in amounts greater than 30 kg/ha per season, regardless of the sources (gypsum, single superphosphate, and/or powdered elemental S), even in areas with low soil nutrient content (Zancanaro et al., 2019).

Table 22. Interpretation of sulfur (S) analysis in soils of the *Cerrado* region, considering the average content in the 0 to 40 cm depth layer.

Sulfur in soil *average between 0-40 cm*\1	**Sulfur availability**
mg/dm^3	
≤ 4	Low
5 - 9	Medium
≥ 10	High

\1 [(sulfur content in the 0-20 cm layer + sulfur content in the 20-40 cm layer)/2]; S extracted with $Ca(H_2PO_4)_2$ 0.01 mol/L in water (soil solution ratio of 1:2.5).
Source: Rein; Sousa (2004).

Micronutrients

Boron, copper, manganese, zinc, and iron

The micronutrient availability classes in soil, based on Mehlich-1, DTPA-TEA, and hot water extractants for soybean cultivation, are presented for soils in Paraná (Table 23), São Paulo (Table 24), and the *Cerrado* region (Table 25). Foliar diagnosis (Tables 3, 4, 5, 6) should be used as a complementary tool for assessing soil micronutrient availability, providing greater precision in diagnosis, regardless of symptom presence.

Table 23. Interpretation limits for micronutrient levels in soils of Paraná state.

Faixas	Extractant			
	Hot water	Mehlich-1		
	B[1]	Cu[2]	Mn[3]	Zn
	---------------------------- mg/dm³ ----------------------------			
Low	< 0.30	< 0.80	< 15	< 1.1
Medium	0.30 – 0.60	0.80 – 1.70	15 - 30	1.1 – 1.6
High	> 0.60	>1.70	> 30	> 1.6

Source: [1]Modified from Galrão (2004); [2]Modified from Borkert et al. (2006); [3]Modified from Sfredo et al. (2006).

Table 24. Interpretation limits for micronutrient levels in soils of São Paulo state.

Faixas	Extractant				
	Hot water	DTPA-TEA			
	B	Cu[2]	Fe	Mn[3]	Zn[1]
	---------------------------- mg/dm³ ----------------------------				
Low	< 0.20	< 0.30	< 5.0	< 1.5	< 0.6
Medium	0.20 – 0.60	0.30 – 0.80	5.0 – 12.0	1.5 – 5.0	0.6 – 1.2
High	> 0.60	> 0.80	> 12.0	> 5.0	> 1.2

Source: Boaretto et al. (2022).

Table 25. Interpretation limits for micronutrient levels in soils of *Cerrado* region, for annual crops.

Faixas	Extractant			
	Hot water	Mehlich-1		
	B	Cu	Mn	Zn
	--------------------------- mg/dm³ ---------------------------			
Low	< 0.30	< 0.5	< 2.0	< 1.1
Medium	0.30 – 0.50	0.5 – 0.8	2.0 – 5.0	1.1 – 1.6
High	> 0.50	> 0.8	> 5.0	> 1.6

Source: Adapted from Galrão (2004).

Table 26 presents recommended micronutrient rates and application methods in soil for correcting nutrient deficiencies.

Table 26. Recommendation for micronutrient application rates in soil for soybean cultivation.

Teor	B	Cu	Mn	Zn
	-------------------------------- kg/ha --------------------------------			
Low\1	2.0	2.0	6.0	6.0
Medium\2	0.5	0.5	1.5	1.5
High	0.0	0.0	0.0	0.0

\1 Broadcast application in a single rate or divided into three equal parts, in the planting furrow, over three successive crops. \2 Broadcast application. Source: Galrão (2004).

Except for manganese (Mn), whose deficiency is induced in soils with high pH or from recent lime application, micronutrient deficiency symptoms are rarely observed under field conditions. In well-drained soils, a significant reduction in plant-available Mn levels due to increased soil pH can be explained by the fact that, theoretically, the concentration of the Mn^{2+} ion decreases 100-fold for each one-unit increase in pH (Barber, 1995). Manganese deficiency is characterized by interveinal chlorosis (coarse reticulation) in the upper third leaves, and it often appears in the early growth stages of soybean cultivated in areas with recent surface liming (Figure 19). Foliar analysis confirmed the diagnosis in a field in Japira, Paraná state, which showed 11.2 mg/kg of Mn, and in Alto Taquari, Mato Grosso state, with only 8.1 mg/kg of Mn.

Of all the micronutrients, boron (B) requires the greatest monitoring and evaluation of management strategies and fertilization recommendations. However, it is not common to observe deficiency symptoms of this nutrient in soybean, even in soils with low levels of available B.

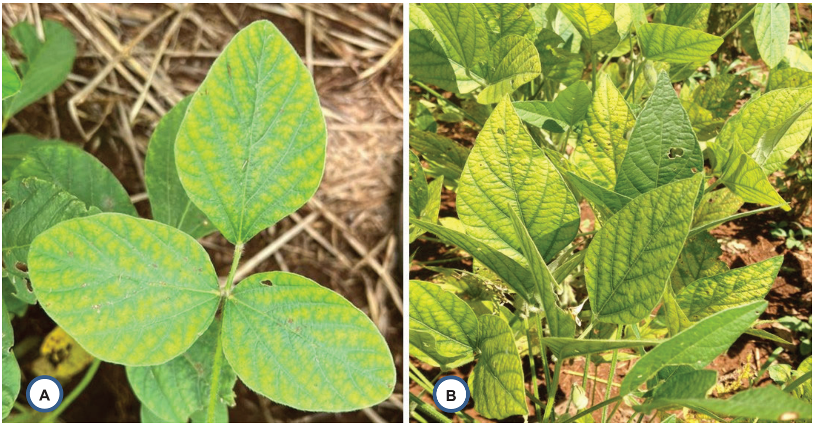

Figure 19. Soybean leaves with visual manganese deficiency, confirmed by foliar analysis, in soybean fields in Japira, Paraná state (A) and Alto Taquari, Mato Gross state (B).

Boron deficiency is more frequent in sandy soils with low organic matter content. Furthermore, conditions of water deficit, particularly characteristic of the autumn/winter period in Brazil, can exacerbate the deficiency of this nutrient. Castro et al. (2014) noted that the distribution of water during the crop cycle is important for boron absorption by the roots. Under conditions of water deficit, adult sunflower plants grown in succession to soybean exhibited characteristic symptoms of B deficiency, such as browning of the upper leaves and, in more severe cases, stem breakage near the inflorescence (Figure 20).

Based on the diagnosis of boron deficiency through soil analysis (Tables 23 to 25) or plant tissue analysis (Tables 3 to 6), corrective fertilization should be performed, using either exclusive sources of the nutrient or fertilizer formulations containing B. However, in most cases, the formulations available on the market do not have a sufficient concentration of B to correct the deficiency in a single application.

Figure 20. Sunflower plant showing severe symptoms of boron deficiency.

In addition to the B deficiency correction recommendations found in Table 26, another option is to apply boron dissolved in the spray mixture of desiccant herbicides (Brighenti et. al. 2006; Castro; Brighenti, 2007; Brighenti; Castro, 2008). This technology combines two objectives in a single spraying operation, where the application of B over the total area is carried out uniformly, without interfering with the efficiency of weed control by glyphosate, whether in pre-sowing desiccation or post-emergence in glyphosate-resistant soybean cultivars.

Products such as glyphosate and potassium glyphosate can be applied in conjunction with boric acid (H_3BO_3) which contains 17% B, or with disodium octaborate ($Na_2B_8O_{13}.4H_2O$), which contains 20.5% B. In the mixture, the fertilizer sources serve solely to supply boron to the plants and, in some cases, to correct the nutrient deficiency in the soil over time. Considering the low B requirement of soybean crops, around 300 g/ha (Table 6), this technology allows for the application of boron quantities that meet plant needs.

One of the precautions when using mixtures, in addition to application or B sources, is to observe the solubility of the sources, a property that determines the maximum rate to be applied based on the volume of the spray mixture. The solubility of boric acid in water is 63.5 g/L (Weast; Astle, 1982; Schubert, 2011), and that of octaborate is 220 g/L (Lopes, 1999), both measured at 30°C. The solubility of boric acid determined at 25°C is 55.2 g/L (Castro; Brighenti, 2007), and Scherer et al. (2011) report that the solubility of octaborate in water is 95.0 g/L. Due to the significant variation in solubility of the sources based on temperature and other molecules present in the spray mixture, the amount of B added should be limited, even from sources with higher solubility, to avoid precipitation problems and clogging of spray nozzles or incompatibility from mixture issues, and even toxicity.

As a practical rule, maximum amounts and safe dilution ratios for the application of boric acid and sodium octaborate in solution are presented (Table 27). This way, it is possible to more accurately determine the minimum volume of spray mixture to be applied based on the B rate or the available fertilizer source (boric acid or sodium octaborate).

Table 27. Calculation of the minimum mixture volume for the dilution and application of boric acid or disodium octaborate.

<table>
<tr><th></th><th>BORIC ACID</th><th>Na-OCTABORATE</th></tr>
<tr><td rowspan="2">Volume of the application mixture (L)=</td><td>B rate (g) x 0.15</td><td>B rate (g) x 0.05</td></tr>
<tr><td>Boric acid rate (kg) x 25</td><td>Octaborate rate (kg) x 11</td></tr>
</table>

Despite the recommendation for correcting B deficiency in the soil, studies conducted with nutrient application via soil and foliar methods in soybean (Castro et al., 2004) and via soil in various years and locations (Oliveira Junior et al., 2018) did not result in significant responses to fertilization in different grain crops. Research conducted in Londrina, Paraná state, using boric acid, Inkabor, and ulexite, and B rates of 0, 2, 4, 8, and 16 kg/ha, broadcasted on a clay soil (~780 g/kg clay) with an initial B content of 0.28 mg/kg, aimed to evaluate the response of soybean and wheat cultivated in succession to the nutrient application via soil over 6 harvests and 10 crops. No increase in yield, deficiency symptoms, or toxicity symptoms were observed, even at the highest B rates in the crops (Castro et al., 2023).

On the other hand, B toxicity can occur in soybean crops grown in sandy soils under temporary water restriction, particularly when fertilized with high rates of B in the planting row, as observed in Figure 21. These plants were fertilized with 1.2 kg/ha of B (A) and 0.85 kg/ha of B (B), and foliar analysis indicated accumulations of 175 and 214 mg/kg of B, respectively.

Figure 21. Symptoms of boron toxicity in soybean crops grown in sandy soil and fertilized with 1.2 kg/ha and 0.85 kg/ha of B in the planting row.

The symptoms of B toxicity are characterized by a gradient in the plants, with more severe symptoms in the older leaves and milder symptoms in the younger leaves (Figure 22). Boron accumulates in the older tissues due to its low mobility and translocation within the plants. Depending on the amounts of B applied to the soil and, primarily, on soil texture and precipitation volumes, the concentration of B in the soil solution can be reduced, allowing the plants to resume normal growth without severe consequences.

Figure 22. Symptoms of boron toxicity in soybean leaves (214.2 mg/kg) cultivated in sandy soils, with fertilization of 0.85 kg of B in the planting row.

Cobalt e molybdenum

Cobalt (Co) and molybdenum (Mo) are essential nutrients for the process of biological nitrogen fixation (BNF). Because of soil pH on nutrient availability (Figure 1), the highest likelihood of response to molybdenum occurs in acidic soils, while the availability of cobalt decreases in excessively limed soils.

The availability of these nutrients in the soil is not routinely determined in soil and plant analyses, and there are no solid studies on response thresholds and interpretation ranges. Therefore, as a precaution, it is recommended to apply at least the minimum quantities potentially exported by the soybean crop each growing cycle.

Molybdenum deficiency symptoms are very rare, even in very acidic soils. However, under these conditions, these symptoms are more easily observed in sunflower plants. The availability of Co determines the efficiency of BNF, but plants do not exhibit deficiency symptoms, as this element is not essential to plant metabolism. On the other hand, the application of cobalt in seed treatment can induce temporary iron deficiency in soybean seedlings (Figure 23), especially in more sensitive cultivars. Nonetheless, the characteristic yellowing occurs on the unifoliolate leaves (V1) and tends to disappear by the time the first trifoliate leaf (V2) emerges.

Figure 23. Soybean seedlings showing symptoms of iron deficiency caused by cobalt.

The technical recommendations for these nutrients suggest applying 2 g/ha to 3 g/ha of Co and 12 g/ha to 25 g/ha of Mo. These rates can be applied with equal effectiveness either through seed treatment or foliar spraying during the V3 to V5 growth stages.

Fertilization Balance as a Recommendation Criteria - AFERE software tool

The fertilization balance involves calculating the difference between the quantities of nutrients applied and those removed by a crop (Figure 24). It allows for assessing the nutrient input and output in a field or farm. Negative balances indicate that the amounts applied were lower than those removed (inputs < outputs), while positive balances indicate that the inputs exceeded the outputs (inputs > outputs). It's important to note that consistently negative balances lead to a reduction/depletion in nutrient levels in the soil, and the magnitude of this reduction is directly proportional to nutrient concentration in the grains and the yields achieved.

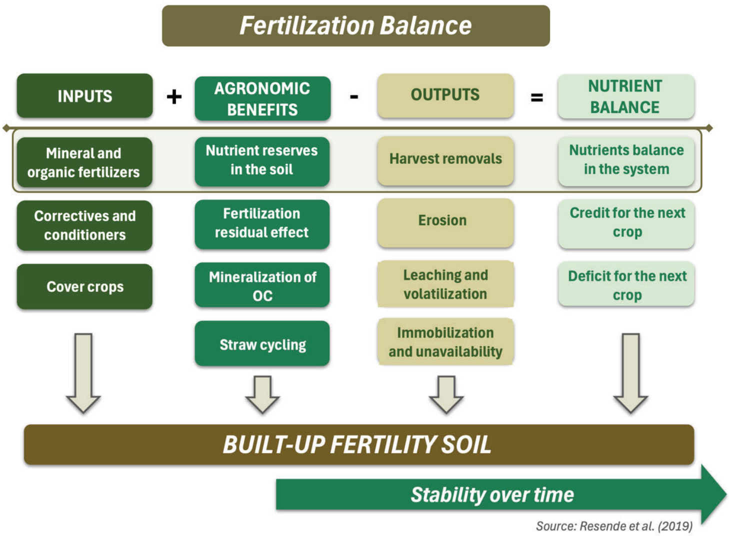

Figure 24. Schematic representation of the fertilization balance.
Source: Resende et al. (2019)

In this context, crops with high protein content, such as soybeans, tend to have higher nutrient concentrations in the grains than crops rich in carbohydrates (e.g., corn and wheat). Therefore, they should be prioritized when balancing production systems.

In areas where nutrient levels are interpreted as high or very high, the balance can mainly serve as an indicator for adjusting nutrient recommendations to ensure proper replenishment (Figure 25). It's also important to highlight that the genetic materials (cultivars/hybrids) available to farmers have high yield potential, which necessitates replenishing nutrients at levels compatible with the achieved yields.

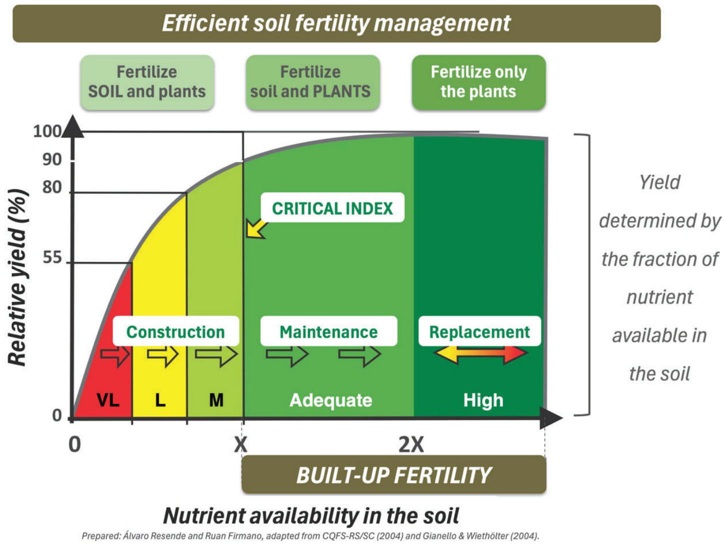

Figure 25. Soil fertility levels as a function of relative yield and efficient fertilization strategies.

Source: Adapted from Gianello & Wiethölter (2004).

To this end, the AFERE platform — Soil Fertility Evaluation and Fertilization Recommendation — was developed, providing tools for interpreting soil analyses and foliar diagnosis, as well as for calculating the fertilization balance in relation to achieved yields and the average values of nutrients accumulated by grains. As a result, the platform indicates the need for fertilization, aiming at least to replenish the nutrients removed from the soil and exported by the grains.

Since soybeans are part of different production systems, often rotated or sequenced with corn and wheat, AFERE compiles information on various crops and calculates the fertilization balance for each crop and the overall production system. In this way, AFERE integrates the information and provides technical recommendations tailored to different production systems, helping to avoid negative fertilization management practices that reduce soil nutrient availability and limit crop productivity due to nutrient deficiency or imbalance, as well as excessive nutrient application, which impacts production costs and agricultural profitability.

From a technical standpoint, the AFERE platform is supported by an updated database, parameterized based on information generated by research from Embrapa, State Institutes, Research Foundations, as well as Universities and research/consulting groups. This allows the interpretation of results using nutritional standards associated with the current high levels of crop productivity. The platform can be accessed at the following address: www.embrapa.br/soja/afere.

Final Considerations

Fertilization should be carried out based on technical criteria that allow for a correct assessment of soil fertility and enable the efficient use of fertilizers, meeting the nutritional needs of plants and maximizing economic efficiency for the farmer. The evaluation of soil fertility is based on identifying nutritional factors that limit high productivity, through chemical soil analysis, which can be complemented by foliar diagnosis.

Chemical soil analysis, the history of soil fertility management and crops, and productivity goals should be the main technical criteria for making fertilization decisions. It is interesting to note that in Brazil, there are official networks of accredited laboratories for soil and plant tissue analysis that serve the main agricultural regions of the country. However, despite the increased use of soil analysis, it is common for it to be primarily employed for soil correction and fertilization with P and K, neglecting other nutrients. For example, even when macro and micronutrient analyses are conducted in the soil, the levels of other nutrients are not rigorously observed and interpreted, leading to inadequate solutions to problems; as if Liebig's "Law of the Minimum," formulated in 1840, were no longer in effect.

Although few farmers utilize foliar analysis, it is an effective practice for assessing the nutritional status of plants and for adjusting and measuring the efficiency of fertilization management. Interpretation standards can be customized regionally and for specific production environments. Additionally, integrated methods (DRIS, CND) allow for the evaluation of nutritional balance based on relationships between nutrients. Grain analysis also provides precise information on nutrient exportation and becomes essential for improving efficient fertilization strategies.

Finally, digital platforms greatly assist in organizing data and processing information, but technical knowledge is fundamental for integrating production factors and defining effective soil fertility management strategies.

Acknowledgments

The authors thank FNDCT/CT-AGRO/FINEP (n. 01.22.0080.00, Ref. 1219/21), for the financial support.

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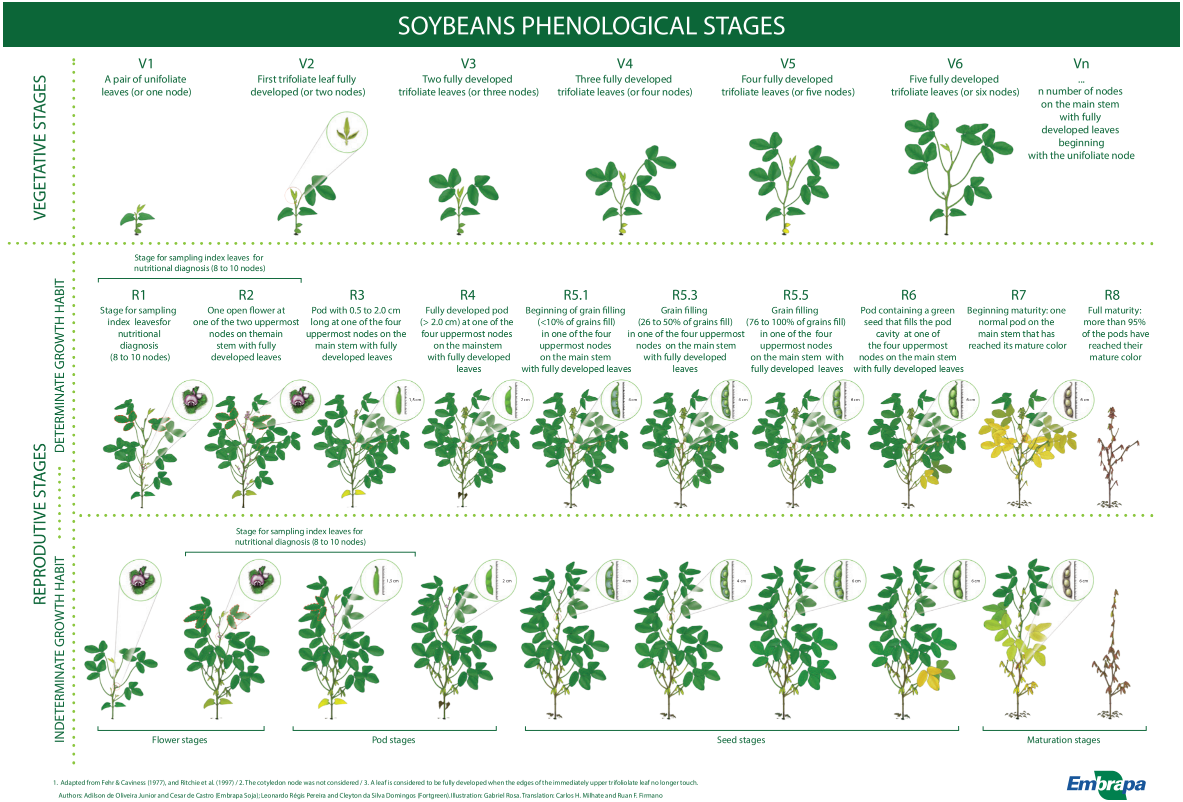
Annex 1. Phenological stages of soybean.



Source: Oliveira Junior et al. (2016).

Embrapa