Chapter 9

Mineral Nutrition and Fertilization of Sugarcane

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Abstract

Sugarcane extracts large amounts of nutrients from the soil and accumulates them in the plant due to its large mass production. Thus, agricultural practices ensuring adequate supply of nutrients to the crop must be adopted to obtain high crop yields in the cane plant cycle and small decreases in the subsequent cycles. In this chapter, the following items will be addressed and discussed: soil sampling, soil fertility evaluation, liming, plastering, cane plant chemical fertilization, sprout chemical fertilization, sugarcane nutritional status evaluation, organic fertilization, use of cultural remains and residues from sugar and alcohol industry, use of humic substances, fertilization, and quality of the sugarcane broth.

Keywords: production system, liming, mineral fertilization, nutritional status, green manure, crop residues

1. Introduction

Sugarcane is a crop adapted to tropical and subtropical climates, developing well between 37° N in southern Spain and 31° S in the Republic of South Africa. It is planted at altitudes ranging from sea level up to 1.00 m. In addition to the production of sugar and alcohol, sugarcane has been widely used by small and medium-sized rural producers for the production of *cachaça*, *rapadura* (raw brown sugar) and brown sugar, as well as for the feeding of ruminants and pigs, especially during times of high purchase price of corn or of low sale value of this monogastric. In order to increase the productivity of inputs, land and agriculture, agricultural techniques have been adopted, among which we may mention the improvement of soil physical and chemical properties by the application of lime and gypsum, chemical fertilization, green fertilization, and use of organic compounds. The choice of sugarcane varieties with a greater productive potential is another technology adopted by producers. For this, it is recommended to consult local or regional research agencies, as well as sugar mills and distilleries, to seek information on the adaptation and productivity of sugarcane varieties in different environments and different cultural managements [1].

The average yields of sugarcane, including dry leaves and buds, oscillated around 100 tons of natural matter per hectare. However, by planting improved varieties and correcting and maintaining soil fertility by applying lime, gypsum and fertilization, it is possible to reach productivities of more than 150 tons of natural material per hectare. Complementary irrigation, especially that performed after sugarcane cutting, has resulted in high productivities and greater longevity of sugarcane plantations, as verified by authors in studies conducted in Paracatu, northwest of Minas Gerais, where they obtained an average productivity in two cuts of over 200 tons of industrializable culms per hectare per year [1].

In order for sugarcane to have high stalk yields in the plant cane cycle and small decreases in ratoon yields, it is necessary to implement measures to maintain or increase soil fertility. Based on that, the present chapter aims to discuss the main technologies, related to soil fertility and mineral nutrition of plants, used for sugarcane production.

2. Nutritional efficiency

Research has shown that there is a difference among sugarcane varieties in terms of efficiency in the absorption and use of nutrients. There are materials presenting a reasonable production even under conditions of low availability of such nutrients in the soil solution, while other varieties, at times more productive, are consequently more demanding. In the analysis of nutritional efficiency of a variety of sugarcane, its capacity to absorb and use nutrients for the production of dry biomass, protein and sucrose is quantified. The variety that, in the same soil and climatic conditions, accumulates more nutrients is considered more efficient in the absorption process, and the variety that produces a greater mass of sucrose or biomass in relation to mass of an absorbed nutrient is the most efficient in the use of such element [1]. It is desirable that the variety be efficient in both processes, but this is not always achieved.

Currently, there are several sugarcane cultivars with good agronomic, industrial and zootechnical characteristics, such as adaptation to different edaphoclimatic environments, erect growth and resistance to falling, which facilitates harvesting, high yield of culms and sucrose, vigor of sprouts, tolerance to major pests and diseases, and a good dry matter digestibility. It is recommended to plant more than one variety of sugarcane so that, in case of an eventual break of disease resistance or a sudden problem with the cultivar, production will not be significantly compromised. When working with several varieties, varietal management should be adopted to use the good characteristics of each variety to the maximum. Having defined the varieties to be planted, it is necessary to make sure of the quality of seedlings. They should preferably be chosen from nurseries with a good sanity, ages varying between 9 and 12 months, and first, or at most, second cutting.

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3. Evaluation of soil fertility

Sugarcane, because it produces large amounts of mass, consequently extracts and accumulates a great quantity of nutrients from the soil. In studies conducted in Brazil, Australia, India, and Florida, it was found that for a production of 120 tons of natural matter per hectare, corresponding to about 100 tons of industrializable culms, the accumulation of nutrients in plant shoots must be 150, 40, 180, 90, 50, and 40 kg of N, P, K, Ca, Mg, and sulfur, respectively. In the case of the micronutrients iron, manganese, zinc, copper, and boron, the accumulations in shoot biomass, also for a production of 120 t, are around 8.0, 3.0, 0.6, 0.4, and 0.3, respectively [2–4]. **Figure 1** shows the accumulation rate of macronutrients in the shoot biomass of RB867515 planted in February and harvested in July of the following year ("year and a half sugarcane").

Due to the high removal of nutrients by the sugarcane harvest, the nutrient supply capacity of the soil must be known to complement chemical and organic fertilization if necessary and, if there is presence of elements at toxic levels, to reduce its concentration by applying lime and gypsum. Normally, nutrient availability and presence of elements at toxic levels in the soil are evaluated by chemical soil analysis. The history of the area, especially fertilizations carried out, and whether or not there were symptoms of deficiency or of toxicity in previous cultures are also of great value [1, 2].

Usually, soil samples are collected from the layers 0–20 and 20–40 cm. The results of the analysis of the layer 0–20 cm will be used to calculate fertilization and liming, and the results of the layer 20–40 cm may be used for calculations of gypsum needed. In the traditional soil sampling system, the area is divided into homogeneous units, taking into account, among others, the history of the area, soil types (color, texture and depth), location and topography (lowlands, slope and plateau), vegetation cover, and previous fertilizations. The most commonly used instruments for collecting soil samples are augers and cutting blades, also known as straight blades. The use of augers in replacement for straight blades has the advantage of a greater speed in collecting

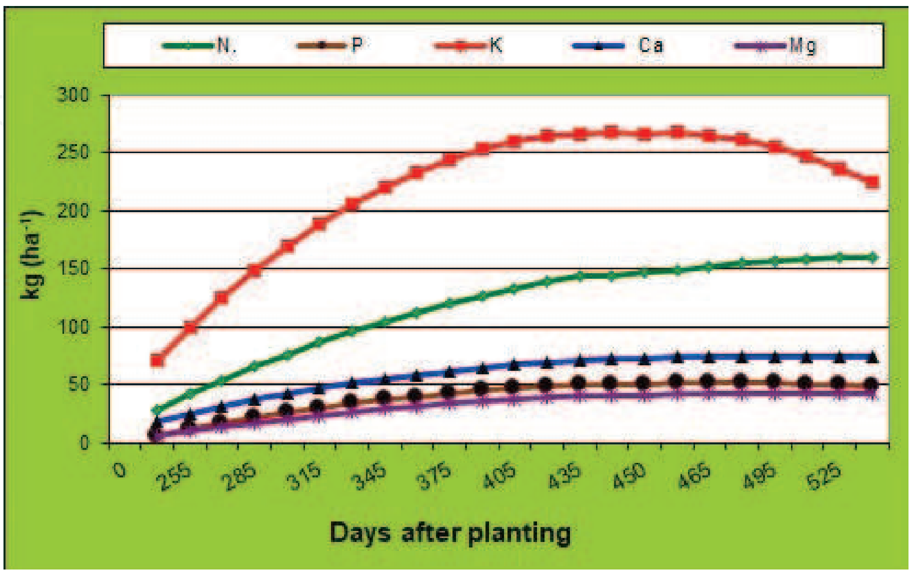

Figure 1. Rate of nutrient accumulation in the shoot biomass of RB67515 planted in February and harvested in July of the following year ("year and a half sugarcane").

simple samples, in handling and transporting a small soil volume in field before homogenization of simple samples, and in collecting composite samples. On the other hand, a low volume of collected soil causes variability of soil fertility indexes to increase, making it necessary to collect a high number of simple samples to form a representative composite sample. Even so, the laboriousness of soil sampling using augers is less than when using straight blades. At first, the use of instruments that collect a small soil volume, such as augers, would not be recommended for areas of minimal or no-tillage, where fertilization is performed in planting lines, preferring in such cases straight blades [1]. Regardless of the material used for sampling, care should be taken to always remove the same soil volume from each single sample.

In large areas, grid soil sampling has been used. This technique consists in the collection of georeferenced soil samples. Due to georeferencing, it is possible to measure the variability of soil nutrient contents and to apply acid and fertilizer correctives at variable levels. In the traditional collection system, to obtain a composite sample, one must collect between 10 and 30 simple samples, numbers that depend on the size of the area and its homogeneity. On average, five simple samples per hectare are collected. After air-drying the composite sample, approximately 500 g of soil is collected to be packed in a properly identified container and sent to a chemical analysis laboratory.

In Brazil, potassium, calcium, magnesium, sodium, and aluminum are analyzed as for exchangeable contents, and even though there is a great variation in the chemical extractors used by different laboratories, the accuracy of such analyses is high. Phosphorus, however, presents a greater reactivity with the soil, and its dynamics is also more complex. Thus, there are questions about the results of analyses performed in laboratories using different methods and extractors. However, analyses carried out by authors on soils from sugarcane regions in the state of Minas Gerais, Brazil, not fertilized with natural phosphate, indicated that there was no significant difference between available phosphorus levels extracted using Mehlich in relation to levels obtained using ion exchange resin. Sulfur and micronutrient contents varied greatly in relation to method and extractor used in soil chemical analysis, and there is still a great influence of collection time, soil moisture, and sample preparation [5]. Thus, the history of the area is of great value, especially regarding micronutrients, because if there is a record of deficiency in previous crops, it becomes necessary to include such deficient elements in fertilization.

4. Liming

Most soils cultivated with sugarcane in the world are acidic, presenting a low saturation by basic cations such as calcium, magnesium, and potassium. Deficiency of basic cations, associated with high levels of aluminum, iron, and manganese, is detrimental to the growth of the root system and, consequently, of the sugarcane plant as a whole. $Al(OH)_2^+$ and Al^{3+} are phytotoxic forms of aluminum that affect cell division, inhibit root growth, cause phosphorus precipitation both in the soil and inside roots, decrease the absorption of water and nutrients, and affect photosynthesis and, consequently, crop productivity. After applying limestone, there is an increase in the soil pH, and a neutralization of soil acidity precipitates aluminum and makes phosphorus available. Studies conducted by [6] on Purple Latosol showed that a pH increase from 4.0 to 5.0 precipitates aluminum totally and raises the phosphorus content from 4.8 to 24.2 mg/dm^3 (**Table 1**).

The use of nitrogen fertilizers, mainly ammoniacal, and the removal of basic cations by harvesting may also contribute to soil acidity, which is why it has been common practice in sugarcane crops to correct soil acidity. Acidification caused by an ammoniacal fertilizer, ammonium sulfate, $(NH_4)_2SO_4$, is exemplified below:

$$(NH_4)_2SO_4 \leftrightarrow 2NH_4^+ + SO_4^{2-} \quad (1)$$

then $2NH_4^+$ originating from the dissociation of $(NH_4)_2SO_4$ is oxidized by Nitrosomonas and Nitrobacter, producing $2NO_3^-$. Thus, the acid reaction of ammonium sulfate can be described as:

$$(NH_4)_2SO_4 + 4O_2 \rightarrow 2NO_3^- + SO_4^- + 2H_2O + 4H^+ \quad (2)$$

Since 100 g of $CaCO_3$ neutralizes 2.0 moles of $2H^+$, to neutralize $4H^+$, 200 g of $CaCO_3$ is required. Several materials can be used as soil acidity correctors. The most used are calcitic limestones, magnesium and dolomitic limestones, and calcium and magnesium silicates, called steel plant slags. In these slags, the magnesium oxide content oscillates around 8%, while calcitic limestones have MgO contents lower than 5%, magnesium levels between 6 and 12%, and dolomitic levels above 12%. The efficiency of these products in the correction of soil acidity depends, among other factors, on their particle size, a uniform distribution in the field, and soil water availability. In relation to the corrective dose, there are some methods to estimate the quantity of product to be applied. Such methods are based on the particle size and neutralizing power of the corrective, as well as soil chemical characteristics, mainly calcium, magnesium, potassium, aluminum, and hydrogen contents.

In the majority of Brazilian states, the corrective dose to be applied is estimated by neutralization of exchangeable acidity and increase in calcium and magnesium contents [7], or base saturation [8]. For sugarcane, it has been recommended to increase base saturation (V) to 60%. According to [8], the amount of limestone (QC) to be used, when adopting the base saturation criterion, is calculated by the following expression:

$$QC\ (t\ ha^{-1}) = [(60–V) \times T]/PRNT \quad (3)$$

pH $CaCl_2$	**Ca**	**Mg**	**K**	**Al^{+3}**	**(H + Al)**	**P**
	(cmolc dm^{-3})					**(mg dm^{-3})**
4.0	1.80	0.66	0.37	1.60	12.56	4.8
4.5	4.40	0.68	0.38	1.00	10.00	5.5
5.0	7.6	0.70	0.35	0.00	6.73	24.2
6.0	10.60	0.70	0.36	0.00	3.66	16.0
7.0	15.00	0.66	0.36	0.00	0.20	8.0

Source: adapted from [6].

Table 1. Neutralization of soil acidity using $CaCO_3$, increase in pH, precipitation of aluminum, and availability of phosphorus from a Purple Latosol.

where V is the current base saturation of the soil, T is the cation exchange capacity at pH 7.0, and PRNT is the relative total neutralizing power of the corrective used.

Studies conducted by [9] on soils cultivated with sugarcane in the Minas Gerais state showed a need to use twice as many corrective levels as calculated using both methods [7, 8] to neutralize exchangeable aluminum or increase base saturation to 60% (**Figure 2**). Results similar to those described by [9] were obtained by [10–12] by comparing analytical methods to assess the need for limestone in the states of Santa Catarina, Paraná, and Mato Grosso. The authors also verified that base saturation underestimated at a high degree the need for limestone by the soils studied, especially the most buffered ones. Base saturation values lower than those predicted analytically were also found by [13] in a medium texture, alkaline Latosol cultivated with sugarcane. Ref. [12] in Campo Novo do Parecis and Nova Mutum (MT) verified that the increase in limestone doses estimated by base saturation ranged from 46 to 92%. Considering the observations of [10–13], the authors recommended that, for areas with base saturation values below 30% or more clayey soils, the amount of limestone to be applied is 1.5–2.0 times as that calculated by Eq. (3) [8].

In large sugarcane crops, many types of limestone distributors have been used, but, for small producers, the application is manual for most of the time. One method that authors have recommended for small producers is to demarcate a square or a rectangle with the limestone itself and, in this area, apply a corrective volume corresponding to the recommended dose. For example, supposing that the recommended dose was 4000 kg and the density of this correction is 1.25 kg/L, then 3200 L of corrective should be applied per hectare, or 0.32 L of the corrective/m^2. One of the options for the producer to manually distribute limestone would be to demarcate 50 m^2 areas with the limestone itself and apply 12.8 L of limestone. In **Figure 3**, a small sugarcane producer is applying limestone using this method to demarcate an area. Two bamboo sticks, spaced 10 m apart, can be seen at the bottom, with a plastic tape tied at the edge to serve as a marking for the demarcation of lines.

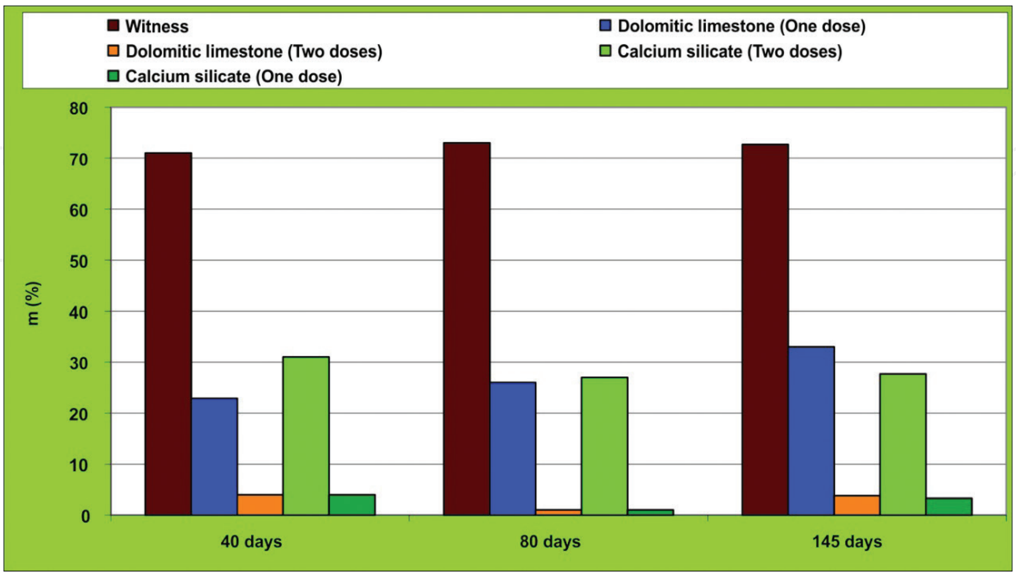

Figure 2. Aluminum saturation (m%) at 40, 80, and 145 days after the beginning of incubation (DAI) of soil samples with dolomitic limestone and calcium silicate using one or two doses of corrective analytically predicted by base saturation.

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Figure 3. Equipment for the distribution of limestone in large sugarcane plantations, and a small rural producer applying limestone to previously demarcated areas.

There is a generalized conceptualization that the best Ca^{+2}:Mg^{+2} ratio in the soil is 4:1. Therefore, the type of limestone (calcitic, magnesian, or dolomitic) to be used should be based on this ratio. On the other hand, some authors recommend exchangeable cation saturation in relation to the effective cation exchange capacity of the soil (t) at 80% of calcium, 13% of magnesium, and 6% of potassium, providing Ca:Mg, Ca:K, and Mg:K ratios of 6.15:1, 13.3:1, and 2.2:1, respectively. However, several studies have shown that the concentrations of Ca and Mg in the solution are more important than the relation between these cations [14]. In the case of corn, studies conducted by [14] indicated that variations in the soil Ca:Mg ratio from 1:1 to 12:1 in soils with exchangeable Ca and Mg contents above 2.32 and 0.40 $cmol_c\ dm^{-3}$, respectively, did not affect yield and production of corn dry matter.

The sugarcane plantation areas and sugarcane planting using minimum and no-tillage systems have increased, following the tendency of corn and soybeans. In these systems, limestone is not incorporated as in the conventional tillage. However, the mineralization of crop remains and sugarcane straw, similar to what occurs in no-tillage areas with annual crops, releases organic anions that complex with Ca, Mg, K, and Al, forming electrically neutral molecules that percolate in the soil. In addition, such organic anions neutralize part of the soil acidity. Therefore, in such areas, liming should be performed only when base saturation at the 0–20 cm layer is lower than 40%.

In a study conducted by [3] using lysimeters, it was verified that the sum of cation charges (K, Ca, Mg, and Na) was always greater than the sum of anion charges (nitrate, sulfate, and chloride) for the whole experimental period. Sulfate was the mineral anion with the highest concentration in the solution percolated in the soil, followed by chloride and nitrate. Initially, organic anions represented only 40% of the total negative charge, but there was a gradual and constant increase of these anions in the ionic balance of the percolated solution and, at the end of the experimental period, their share of the solution's electroneutrality increased to 70%. Such results confirm, as in other studies, that organic anions originating from the mineralization of sugarcane remains or released by sugarcane roots must be involved in the nutrient leaching process by organometallic complexation with Ca, Mg, K, Al, and Na, which are present in the soil solution.

5. Gypsum

Agricultural gypsum, $10CaSO_4.2H_2O$, a by-product of the fertilizer industry, originates from the reaction between sulfuric acid and phosphate rocks used to produce phosphoric acid. Gypsum applied to soil does not neutralize soil acidity but decreases aluminum saturation and increases base saturation of the subsurface, providing conditions for a further development and deepening of the sugarcane root system. It is recommended to apply gypsum when CaC^{2+} contents are lower than 0.4 $cmol_c\ dm^{-3}$ and/or aluminum saturation is greater than 20% at the 20–40 cm layer. The application of gypsum will lead to the improvement of the root environment at layers below arable ones, an effect that lasts for several years. For this reason, the annual reapplication of gypsum is not necessary. In areas with sugarcane straw or organic residues on the soil, and if the contents of Ca^{2+} are not very low and/or aluminum saturation is not very high, the response to gypsum may be lower.

The doses of gypsum to be applied may be based on the need for liming, or on soil texture. The amount of gypsum to be applied varied between 25 and 30% for the need for liming, multiplied by a depth correction factor (profile to be corrected/20). For example, the amount of limestone to be applied was 3.0 t ha^{-1}, and improvement of the root environment at the 20–60 cm layer is desired. Then, the amount of gypsum will be equal to 1.5 t ha^{-1}[(3.0 x 0.25) x (60–20)/20]. When the doses of gypsum to be applied are based on soil texture, the following recommendation can be used [8]: dose to be applied (kg ha^{-1}) = clay (g kg^{-1}) x 6.0.

Gypsum is applied in total area and may or may not be incorporated into the soil. When it is not possible to use it, mainly because of difficulty in acquiring it in small quantities, a fact that usually happens with micro and small farmers, one should choose to apply simple superphosphate as a source of phosphorus because this fertilizer contains calcium sulfate. In a study conducted by [15], limestone and gypsum rates were studied in a sugarcane crop cultivated in medium texture soils with a low cation exchange capacity. A relation between calcium levels in the soil and growth of the root system was also observed. Twenty-seven months after the beginning of the study, in a treatment with the application of 2.8 t of gypsum per hectare, the highest yield of biomass and industrializable shoots occurred. By soil

Layer (cm)	Exchangeable calcium ($cmol_c\ dm^{-3}$)	Root mass (g dm^{-3})	% of root system
0–25	2.10	4.4	29.93
26–50	1.37	3.0	20.41
51–75	0.90	2.4	16.33
76–100	0.82	2.0	13.61
101–125	0.70	1.8	12.24
126–150	0.60	1.1	7.48

Source: adapted from [15].

Table 2. Calcium content in the soil and growth of sugarcane root system in a soil that received limestone and gypsum.

analysis, a relation between exchangeable calcium and sugarcane root system was found: at 150 cm depth, Ca^{2+} was 0.60 $cmol_c/dm^3$ and the root mass was 1.1 g/dm^3. Several authors have reported that under conditions of low availability of calcium in the soil, sugarcane roots concentrated at the layer 0–30 cm. However, in this study, 50% of the root system mass was in the layer 51–150 cm (**Table 2**).

6. Liming in sugarcane regrowth areas

Soil calcium and magnesium contents decrease during sugarcane cycles both by the removal of bases by harvests and by acidification caused by nitrogenous fertilizers. This effect is demonstrated in the long-term study (**Figure 4**) conducted by [15, 16]. These authors evaluated the reacidification of a soil cultivated with sugarcane by five cuts.

Initially, the soil presented, at the layers 0–20 and 20–50 cm, a base saturation of 15 and 7%, respectively. At the time of preparation of the soil for planting sugarcane, 2.5 t of limestone and 1.5 t of gypsum were applied per hectare. Soil chemical changes in plant cane and regrowth are shown in **Figure 4**. After plant cane thinning, base saturation at the layers 0–20 and 20–50 cm was, respectively, 52 and 38%; by the fifth cut, the values were similar to those observed at the time of reforestation.

The authors of this chapter have recommended liming for regrowth areas when there is a base saturation of less than 50% at the 0–20 cm layer. The application of corrective should be in the total area preceding crop treatments and calculating the necessary amount as previously described.

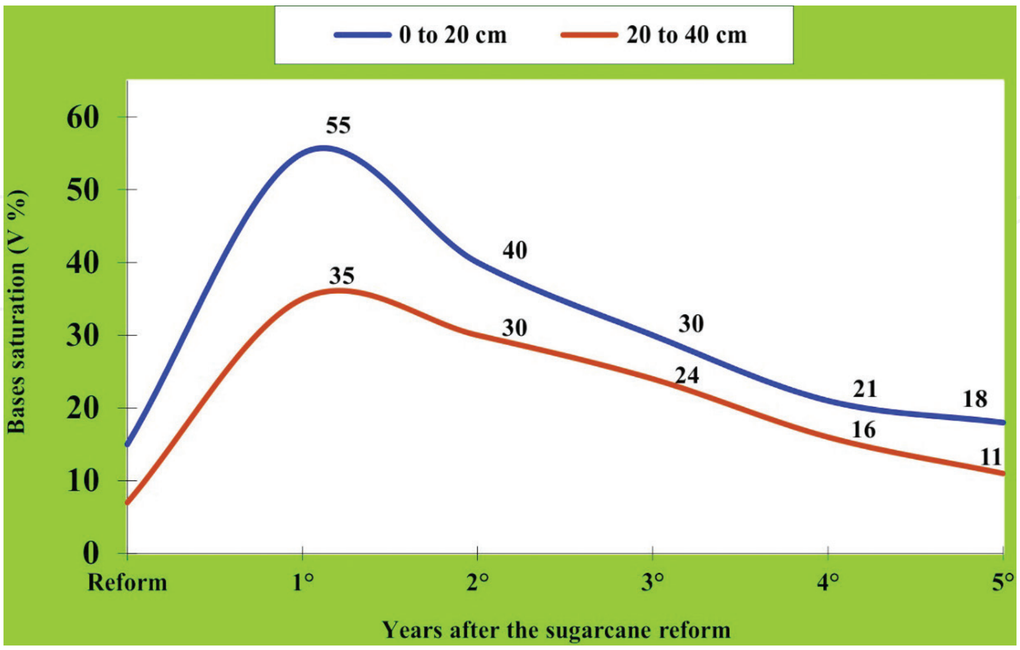

Figure 4. Changes in the base saturation of a soil cultivated with sugarcane. Source: adapted from [15, 16].

7. Mineral fertilization

The mineral fertilization of sugarcane is based on the results of soil analysis at the 0–20 cm layer and on the productivity desired.

7.1. Nitrogen in plant cane

Nitrogen is important for the nutrition and physiology of sugarcane because, among other functions, it is a constituent of all amino acids, proteins, enzymes, and nucleic acids [17]. Nitrogen and potassium are absorbed in greater amounts by this crop [3]. The absorbed nitrogen increases the meristematic activity of shoots, resulting in greater tillering and leaf area index (LAI). Furthermore, N increases leaf longevity. Such an increase in LAI increases the efficiency of use of solar radiation, measured as the fixation rate of carbon dioxide (μmol of CO_2 m^{-2} s^{-1}), thus increasing accumulation of dry matter.

The accumulation of nitrogen by sugarcane varies according to cultivar, crop age, and availability of N and other elements in the soil solution and also depends on soil and climatic factors. For the more common varieties planted, nitrogen extraction ranges around 1.2 kg per ton of natural matter of shoots. Considering that roots and rhizomes correspond, on average, to 30% of the mass of the whole plant, it can be estimated that for each t of natural matter accumulated by shoots, there is an absorption of 1.5 kg of N by the plant. Therefore, for systems with a productivity greater than 120 tons of natural matter per hectare, the amount of N absorbed by the crop exceeds 180 kg ha^{-1}. In these systems, the use of nitrogen fertilization at doses ranging from 60 to 100 kg ha^{-1} is suggested [1].

Nitrogen uptake and nitrogen metabolism are greatly influenced by phosphorus availability. In plants with inadequate phosphorus supply, there is a decrease in the nitrate absorption of the soil solution. The nitrate translocation from roots to shoots decreases, thus increasing the accumulation of amino acids in leaves and roots. Ref. [18] observed an enormous influence of the availability of P, both of nutrient and endogenous solution, on corn nitrogen uptake and metabolism (**Figure 4**). Well-supplied phosphorus plants before and during a kinetic study (+P; +P) showed a practically constant nitrate absorption during the experiment. However, plants deprived of P before and during the experimental phase (−P; −P) were unable to absorb the nitrate from the solution.

It is believed that plant cane, because it has a higher phosphorus supply when compared to regrowth, behaves similar to corn plants well supplied with phosphorus (+P; +P). In studies conducted by the authors in the region of Passos, southern Minas Gerais, it was verified that the increase in the dose of phosphorus applied to planting grooves affected larger accumulations of N in the biomass of plant cane, since for each kg of P applied there was an increase of about 1 kg of N. These results are certainly the effects of changes caused in the absorption and metabolism of nitrogen, as observed by [18].

It should be noted, however, that some studies reported a low response of plant cane to nitrogen fertilization, and the causes of such low responses are not sufficiently explained. Several authors have attributed it to experimental variability, to mineralization of organic matter and of crop remains, to fertilizer application times, and to losses by leaching and denitrification

[19, 20]. However, in an experiment conducted by [3] with plant cane cultivated in a sandy soil and fertilized with marked urea (^{15}N), losses were not observed with the leaching of nitrogen from the fertilizer (**Figure 5**). The movement of the ^{15}N-fertilizer was small. More than 70% of the fertilizer recovered in the soil was at the 0–30 cm layer. There was a measurable loss of N native from the soil, or of crop remains, equivalent to 4.5 kg ha^{-1} [3]. Thus, if nitrogen fertilization is applied to plant cane, nitrogen fertilizer, at doses ranging from 60 to 100 kg ha^{-1}, should be applied to the bottom of planting grooves along with phosphorus and potassium.

7.2. Nitrogen in regrowth

The responses of sugarcane regrowth to nitrogen fertilization are more frequent than in plant cane, with a percentage above 90%. As a general recommendation, it is suggested to apply 1.0 kg of N per ton of natural matter accumulated in shoots. Since industrializable culms represent on average 80% of the natural matter of shoots, yields of 100 t of culms would correspond to 125 t of natural matter. In this case, the recommendation for fertilization would be 125 kg of N ha^{-1}, and the nitrogen fertilizer should be applied in a single dose together with potassium.

Urea has been the most used nitrogen fertilizer for sugarcane fertilization mainly because of its lower cost per unit of N compared to other sources. The application of urea to the soil or straw may lead to large losses due to the volatilization of ammonia (approximately 40%) [1]. Therefore, it is recommended to bury it into the soil at a depth of approximately 7.0 cm. When it is not possible to bury the urea in the soil, it must be irrigated to incorporate it into the soil or to fertilize it before a rain, which is possible only in small areas. If it is not possible to bury

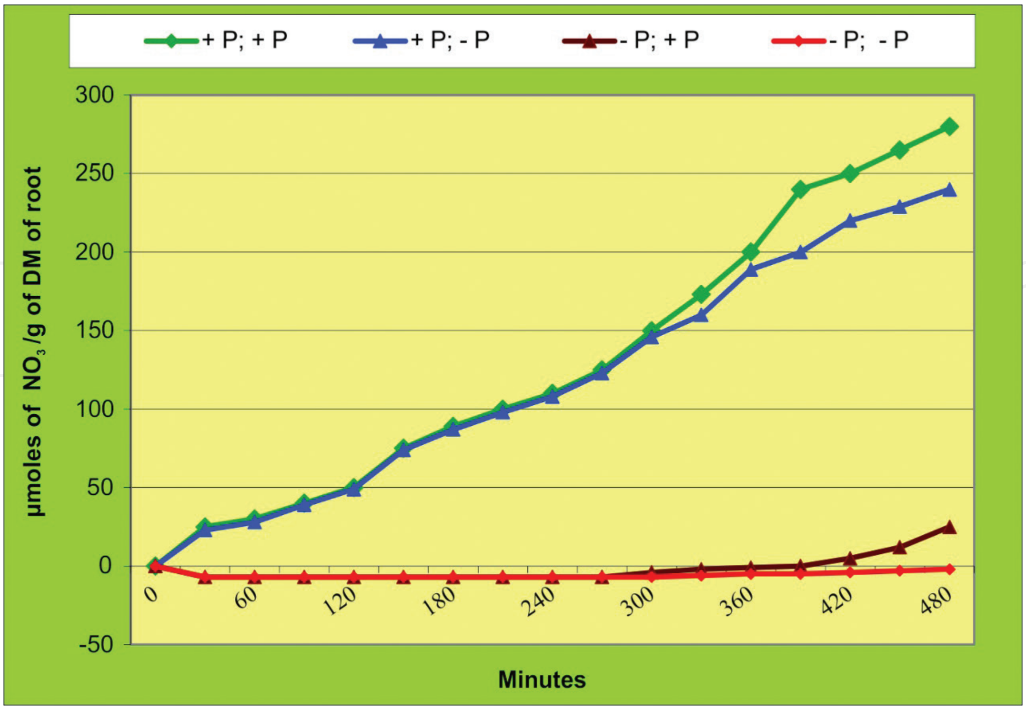

Figure 5. Nitrate uptake by corn plants with different phosphorus supplies: adequate before and during the study (+P; +P), adequate before and absent during the study (+P; −P), absent before and adequate during the study (−P; +P), and absent before and during the study (−P; −P). Source: adapted from [18].

urea in the soil, irrigate it, or fertilize it before a rain, one should choose ammoniacal sources, such as ammonium sulfate, or nitric sources.

7.3. Phosphorus

The highest dose of phosphorus should be applied to the bottom of planting grooves. Such application at a greater depth increases the nutrient uptake by sugarcane, since water availability at the subsurface varies less than on the surface. The mobility of phosphorus in the soil is small, and its diffusion is influenced by several factors, especially precipitation by cations such as iron, aluminum, and calcium; volumetric content of water in the soil; adsorption of phosphorus by soil colloids; complexity of the environment structure; soil compaction; distance to reach roots; and contents of elements in soil [21]. In general, very low values are recorded for transport of phosphorus due to its strong interaction with soil colloids, especially in very weathered soils. According to [21], it can be estimated that the transport is on average 0.013 mm per day.

Even applying a higher dose of phosphorus during planting, there is a need for phosphate fertilization for regrowth. **Tables 3–5** present recommendations for phosphate fertilization of plant cane at the bottom of planting grooves, considering the extractor used in the soil chemical analysis, Mehlich or ion exchange resin, as well as soil fertility classes.

According to some authors, it is unlikely to obtain a productivity above 150 t when the phosphorus extracted with resin is lower than 6.0 mg dm^{-3}. However, in studies conducted in newly developed Cerrado areas in the northwest of Minas Gerais on a phosphorus content lower than 6.0 mg dm^{-3}, yields were higher than 200 tons of culms per hectare in a plant cane with a 14-month cycle fertilized with 100 kg of P per hectare and receiving complementary irrigation of only 120 mm [1].

Phosphorus applied during sugarcane planting ensures, in most cases, an adequate supply of this element to plant cane and the first regrowth. Formulations containing P in the fertilization of later regrowth should be used. Prior to phosphate fertilization, the soil should be analyzed at the 0–20 cm layer and, if the base saturation (V) is less than 50%, it is recommended to perform first a liming to raise the V to 60%. As shown in **Table 1**, the absence of exchangeable aluminum in the soil solution increases the efficiency of phosphate fertilization, especially since there is no formation of aluminum phosphate (a low solubility compound) in the soil

Clay content (g kg^{-1})	Low	Medium	High
	Available phosphorus classification (mg dm^{-3})		
0–150	Less than 20	20–30	Above 30
150–350	Less than 15	15–20	Above 20
350–600	Less than 10	10–15	Above 15
600–1000	Less than 5	5–10	Above 10
	Available potassium classification (mg dm^{-3})		
	Less than 40	41 a 90	Above 90

Table 3. Soil fertility classes considering clay, phosphorus, and potassium contents extracted with Mehlich.

Production expectation in the cane plant cycle (t ha^{-1})	Soil fertility class		
	Low	Medium	High
	Dose of P (kg ha^{-1})*		
Less than 100	70	—	—
100–150	80	60	40
150–180	90	70	50
Above 180	100	80	60

*To convert P into P_2O_5, multiply the desired value by 2.29.

Table 4. Phosphorus doses suggested for sugarcane fertilization based on the availability of phosphorus extracted with Mehlich and on the expectation of natural matter production.

Production expectation in the cane plant cycle (t ha^{-1})	Extracted phosphorus (mg dm^{-3})			
	0–6	7–17	16–40	>40
	Dose of P (kg ha^{-1})*			
Less than 100	80	44	30	20
100–150	90	55	40	26
Above 150	100	66	45	35

*To convert P into P_2O_5, multiply the desired value by 2.29.
Source: adapted from [8].

Table 5. Phosphorus doses suggested for sugarcane fertilization based on the availability of phosphorus extracted with ion exchange resin and on the expectation of natural matter production.

and within plant roots. If the base saturation is greater than 50% and the P content, extracted with Mehlich, is lower than 10 mg/dm^3, a regrowth phosphate fertilization is recommended.

The dose of phosphorus used may be based on the recovery of the P removed by harvesting. In this case, for each ton of natural material, 200–300 g of P should be applied. If, for example, the production of natural regrowth material was 120 t per ha, which corresponds to about 100 t of industrializable culms, from 25 to 40 kg of P should be applied per ha. Phosphate fertilizer should be applied together with N and K. In large crops, regrowth N-P-K fertilization is carried out simultaneously with subsoiling and cultivation of interlines. In small and medium properties, especially those where burnt sugarcane is harvested or produced for animal feed, the furrowing of sugarcane lines using an animal traction plow for later fertilization has presented good results. The N-P-K fertilizer is applied to open grooves in sugarcane interlines and then covered with soil using animal traction.

7.4. Potassium

Potassium fertilization of sugarcane is carried out at planting and after each sugarcane cut because potassium is displaced in the soil profile. The mineral fertilization of sugarcane is based on the results of soil analysis at the 0–20 cm layer, on the productivity desired and on the final use of sugarcane. In sugarcane fields intended for cattle feeding, the potassium dose to be applied should be increased, since nutrient removal will be greater because sugarcane is harvested along with nodes and dry leaves. The amount of potassium contained in nodes and dry leaves of sugarcane ranges around 70 kg per ha [22] and may reach 140 kg per ha in plant cane [3]. **Tables 6–8** present the recommendations of potassium fertilization for plant cane and regrowth, with Mehlich or ion exchange resin as extractors.

The dose of K to be applied to regrowth may be based on the recovery of the potassium removed by the crop, as suggested for nitrogen and phosphate fertilization. This method was adopted by the authors and has been recommended with excellent agronomic and financial results. Although the absorption and the removal of potassium vary among sugarcane cultivars, it can be considered that for each ton of natural matter harvested, there is, on average, a removal of 1.5 kg of K. There is no need to partition the potassium used in regrowth fertilization due to possible losses by leaching. In studies conducted by Oliveira et al. [3] using lysimeters, K losses by leaching were not reported (**Figure 6**). These results were confirmed by [23], who also observed that K losses by percolation below a depth of 100 cm were 9.0 kg ha^{-1}, totally compensated by the input of K from rainwater (18 kg ha^{-1}).

Production expectation in the cane plant cycle (t ha^{-1})	Soil fertility class		
	Low	Medium	High
	Dose of K (kg ha^{-1})*		
Less than 90	100	—	—
90–120	120	100	80
120–150	140	120	100
150–180	160	140	120
Above 180	180	160	140

*To convert K into K_2O, multiply the desired value by 1.20. When sugarcane is harvested for animal feed, it is suggested to raise the recommended K dose by 25%.

Table 6. Potassium doses suggested for sugarcane fertilization based on the availability of potassium extracted with Mehlich and on the expectation of natural matter production.

Production expectation in the cane plant cycle (t ha^{-1})	K extracted with resin (mmol$_c$ dm^{-3})				
	0–0.7	0.8–1.5	1.6–3.0	3.1–6.0	>6.0
	Dose of K (kg ha^{-1})*				
Less than 100	120	100	60	60	0
100–150	160	140	100	80	0
Above 150	200	160	120	100	0

*To convert K into K_2O, multiply the desired value by 1.20.
Source: adapted from [8].

Table 7. Potassium doses suggested for sugarcane fertilization based on the availability of potassium extracted with ion exchange resin and on the expected production.

Regrowth production expectation (t ha^{-1})	K extracted with resin (mmol$_c$ dm^{-3})		
	0–1.5	1.6–3.0	>3.0
	Dose of K (kg ha^{-1})*		
Less than 60	90	60	30
60–80	110	80	50
80–100	130	100	70
Above 100	150	120	90

*To convert K into K_2O, multiply the desired value by 1.20.
Source: adapted from [8].

Table 8. Potassium doses suggested for regrowth fertilization based on the availability of potassium extracted with ion exchange resin and on the expected production.

Figure 6. Solution volume and mass of percolated nitrogen during the plant cane cycle cultivated in a sandy soil.

Potassium chloride has been the most used source of K in fertilization. However, other residues containing potassium are also used, among them vinasse, a by-product of alcohol manufacture. Vinasse may replace potassium fertilization. Therefore, the amount of potassium supplied by application of vinasse should be fully deducted from mineral fertilization. The volume of vinasse applied ranged from 60 to 300 m^3 ha^{-1} depending on the potassium concentration. The concentration of K in vinasse originating from molasses is higher than in others, followed by a mixed must, which contains on average twice as much K as in vinasse originating from sugarcane juice, with values ranging between 2.5 and 1.2 kg m^{-3}, respectively (**Table 9**).

7.5. Sulfur

Sulfur can be dispensed in areas that received application of vinasse or agricultural gypsum. The critical level of S-SO_4^{-2} in the soil, extracted with $Ca(H_2PO_4)_2$ 500 mg L^{-1}, is 10 mg/dl^3. In areas in

Chemical composition	Origin of must		
	Molasses	Mixed	Cane juice
	kg of the element by m^3 de vinasse		
N	0.57–0.79	0.33–0.48	0.25–0.35
P	0.05–0.15	0.03–0.14	0.03–0.07
K	3.27–6.32	1.81–2.78	0.95–1.61
Ca	1.32–1.70	0.40–0.95	0.08–0.52
Mg	0.50–0.85	0.19–0.35	0.13–0.25
S	0.30–0.40	0.45–0.54	0.58–0.70
Organic matter	37.0–57.0	19.1–45.1	15.3–34.7
	g of the element by m^3 de vinasse		
Fe	52–120	47–130	45–110
Cu	3.1–9.3	4.2–57.3	1.0–18.0
Zn	3.0–4.0	3.0–4.0	2.0–3.0
Mn	6.0–11.0	5.0–11.0	5.0–10.0
pH	4.2–4.4	3.6–4.4	3.5–3.8

Source: Analyses carried out by the authors on the vinasse of mills located in Minas Gerais and Alagoas, Brazil.

Table 9. Chemical composition of vinasse originating from different musts.

need of this macronutrient, at least 30 kg of sulfur per hectare should be applied using ammonium sulfate or simple superphosphate, which contains, respectively, approximately 210 and 110 g of S per kg of fertilizer (**Figure 7**).

7.6. Micronutrients

In most areas cultivated with sugarcane in Brazil, there has been an adequate supply of micronutrients in the soil, thus dispensing their use in chemical fertilizations. However, the implantation of sugarcane plantations in less fertile or marginal areas, associated with fertilization using concentrated fertilizers and the planting of high productivity varieties, which increasingly increase the absorption and export of nutrients, has caused micronutrient deficiency in several sugarcane plantations. In such cases, there is a need for the supply of microelements by fertilization. Soil analysis and area and variety history have been used as predictive methods for assessing the possibility of occurrence of micronutrient deficiency. Soil analysis should be associated to area and variety history since analytical results are influenced by the extractor used, by the characteristics of the soil and of the variety, and also by the time of sample collection. There are reports of marked effects of soil moisture on micronutrient contents [1, 5].

Studies carried out by [24] showed that the best correlations between the Zn or Cu contents in soils and the concentrations of these micronutrients in plants were obtained by the method that uses a solution of diethyl triamine penta-acetic acid (DTPA) as extractor when compared

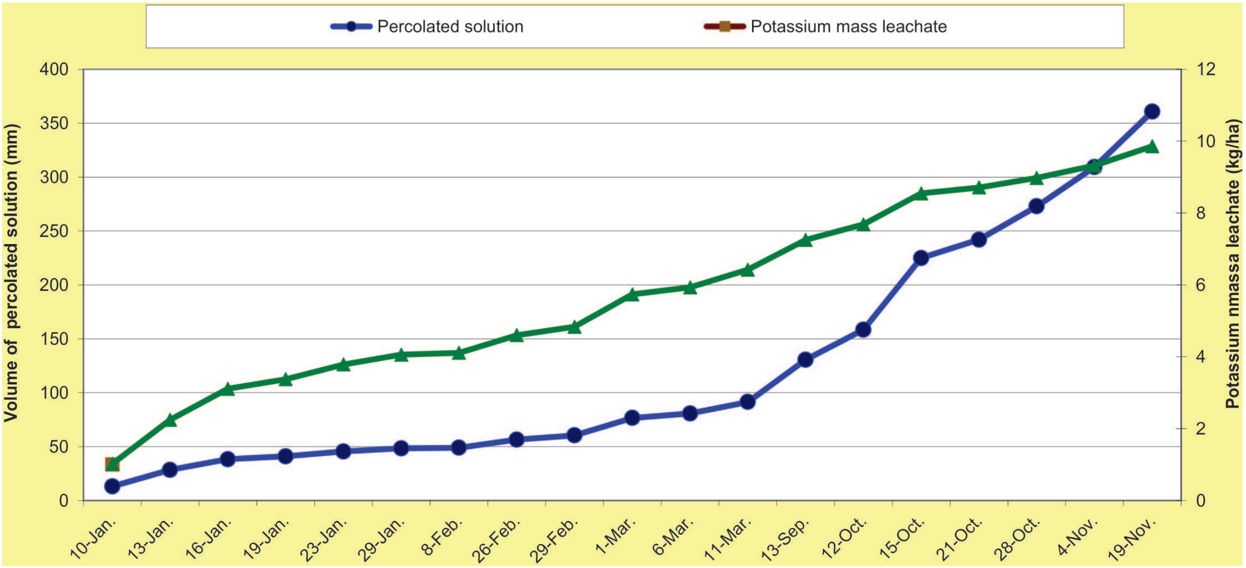

Figure 7. Solution volume and mass of percolated potassium during the plant cane cycle cultivated in a sandy soil.

to Mehlich-1 and HCl extractors. According to [24], there is a tendency for DTPA to be more efficient than Mehlich-1 and HCl in situations where the availability of Zn and Cu is changed by liming. As for Mn, acid and chelating solutions have shown very close correlation coefficients between Mn in soil and in plants. However, by analyzing soils fertilized with Mn oxides, there was a tendency of DTPA being the best extractor.

Table 10 lists the minimum levels of micronutrient availability in soil extracted with DTPA and Mehlich-1 solution, below which such microelements should be supplied to plants by fertilization. The doses of copper, zinc, manganese, and iron to be applied, in case of deficiency, are 2.5–6.0, 5.0–7.0, 3.0–6.0, and 6.0–10.0 kg ha^{-1}, respectively, using oxides, chlorides, and sulfates.

In studies conducted by the authors on coastal plain soils in Alagoas, northeastern Brazil, it was verified that even when high-dose manganese and copper sulfates (up to 16.0 kg of element/ha) were applied, RB867515 and RB92579 remained deficient in these elements. The content

	Extractor							
	DTPA				**Mehlich-1**			
	Element							
Available	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	mg dm^{-3}							
Low	≤0.2	≤0.5	≤1.2	≤4	≤0.8	≤1.0	≤6	≤19
Medium	0.3–0.8	0.6–1.2	1.3–5.0	5–12	0.8–1.2	1.0–1.5	6–8	19–30
High	>0.8	>1.2	>5.0	>12	>1.2	>1.5	>8	>30
Source: cited by [1].								

Table 10. Minimum values of micronutrient availability in the soil extracted with a solution of DTPA and Mehlich-1.

of these nutrients in the +3 leaf limbus, used to evaluate nutritional status, was lower than 5.0 and 40.0 mg/kg of dry matter, respectively, for copper and manganese, characterizing a severe deficiency of these elements. The high adsorption of copper and manganese sulfates may have been the cause of the absence of responses. Ref. [25] studied the adsorption of copper originating from several compounds. These authors studied the application of $CuSO_4$ to sandy and humic soils. They found a very high adsorption (99.4%) of copper 2 h after its addition to the soil. On the other hand, copper in the ethylene diaminotetraacetic acid and diaminocyclohexane tetraacetic acid forms presented a soil percentage adsorption of 7.3 and 5.3, respectively. Therefore, it is necessary to evaluate the efficiency of other sources of copper and manganese because the adsorption of copper and manganese sulfates by the soil was very high. In addition to compromising the productive potential of these varieties, copper and manganese deficiency leads to metabolic changes that compromise the quality of the broth. These nutrients are constituents of the polyphenol oxidase and amylase metalloenzymes [17, 26, 27]. Therefore, with a poor performance of these enzymes, there is accumulation of phenolic and starch compounds.

8. Evaluation of the nutritional status of sugarcane

The chemical analysis of sugarcane leaves is another way for evaluating the nutritional status of crops. The preference for leaves is because, in general, they reflect better the variations in the supply of nutrients both by the soil and by fertilizations. In sugarcane, it has been recommended to collect the +2 or +3 leaves. The leaf +1 is, in the descending direction of the stem, the first leaf to show a fully visible ligule (region of insertion of the leaf sheath on the stem). For the chemical analysis, the median third of the +2 or +3 leaf is used excluding the central vein.

Samples from the middle third should first be washed in clean running water and then in distilled water. Then, the material should be dried at 65°C until constant weight. If this

Authors	Nutrient ($g\ kg^{-1}$)					
	N	P	K	Ca	Mg	S
[17]*	19–21	2.0–2.4	11–13	8.0–10	2.0–3.0	2.5–3.0
[17]**	20–22	1.8–2.0	13–15	5.0–7.0	2.0–2.5	2.5–3.0
[28]	18–25	1.5–3.0	10–16	2.0–8.0	1.0–3.0	1.5–3.0
[29]	16–25	2.0–3.5	6–14	4.3–7.6	1.1–3.6	1.3–2.8
Authors	**Nutrient ($mg\ kg^{-1}$)**					
	B	**Cu**	**Fe**	**Mn**	**Mo**	**Zn**
[17]*	15–50	8–10	200–500	100–250	0.15–0.30	25–50
[17]**	—	8–10	80–150	50–125	—	25–30
[28]	10–30	6–15	40–250	25–250	0.05–0.20	10–50
[29]	6–29	9–17	76–392	73–249	—	—

*Concentration ranges for plant cane.

**Concentration ranges for regrowth.

Table 11. Nutrient concentration ranges in the middle third of the +2 or +3 leaf considered adequate.

drying is not possible, the samples should be sent quickly to the laboratory where they will be analyzed. **Table 11** lists the nutrient concentration ranges considered adequate according to Brazilian researchers.

9. Green fertilization

Green fertilization is the cultivation of plants for the purpose of incorporating them into the soil. Among the desirable characteristics of a plant to be used as green manure, we may mention the possibility of mechanization from sowing to seed harvesting, absence of dormant seeds, vigorous and deep root system, ability to associate with nitrogen fixing bacteria in atmospheric air, fast growth to control weeds, and presence of mechanisms or synthesizing compounds that aid in the control of pests, such as nematodes, and diseases.

Several legumes have these characteristics, but generally there is a preference for *Crotalaria juncea* in the Center-South region of Brazil and for *Crotalaria spectabilis* in the states of Alagoas and Pernambuco, northeastern Brazil. *Crotalaria juncea* is a legume with a very fast initial growth, which provides it with a great competition potential with weeds. However, it is very sensitive to nictoperiods, early blooming in growing nights and, consequently, interrupting growth. Therefore, when cultivating for green manure, sowing should be performed in early October, or as soon as possible. However, for seed production, it should be sown in March.

In studies conducted by [1] in two regions of Minas Gerais, Alto Paranaíba and Zona da Mata, there was accumulation of dry matter (DM) by *Crotalaria juncea* sown in October, around 15 tons per hectare, with nitrogen concentration oscillating around 20 g of N per kg of DM. Thus, for a DM yield of 15 t ha^{-1}, the amount of N fixed and/or recycled is 300 kg per hectare. In areas densely infested with *Brachiaria plantaginea*, the inclusion of *Crotalaria* in the system increased the mass of N over the soil by 320% since the accumulation by the natural vegetation of the fallow area was 66 kg of N per ha, while in the area with *Crotalaria*, this accumulation exceeded 250 kg ha^{-1}, a sufficient quantity to ensure a production of 230 t of natural matter of sugarcane per hectare. Ref. [1] reported that in experiments conducted in areas where *Crotalaria* was incorporated into the soil, there was an increased productivity in plant cane of 15 t of culms per hectare compared to fallow areas.

The dry matter production of *Crotalaria juncea* and *spectabilis* in the states of Alagoas and Pernambuco oscillated around 4.5 t of DM per ha. This low production of DM, compared to that observed in the Center-South region, is mainly because the sowing season occurred at the beginning of the rainy season, between April and early May, therefore in longer nights. In Alagoas, in areas where *Crotalaria spectabilis* is used as green manure, it has been common to perform direct grooving without previous soil plowing, similar to the minimum cultivation systems adopted for some other crops.

10. Crop residues and sugarcane agribusiness waste

Straw is the main crop residue. There are also several types of waste from the industrialization of sugarcane, among them vinasse, filter cake, boiler ashes, and bagasse, which are routinely used in fertilization as sources of nutrients and organic matter. The amount of straw that remains on the soil after the harvest of sugarcane not debrided with fire varies according to cultivar and adopted agricultural practices; such amount ranges from 12 to 18 t ha^{-1} [22]. In studies conducted by [22] in the region of Ribeirão Preto, SP, it was verified that, among the nutrients in straw, only potassium presented a great liberation during 1 year of permanence of this crop residue in field (**Table 12**). Thus, with the exception of K, the nutrients contained in straw will not contribute significantly to the nutrition of sugarcane during the cycle following the cut.

Vinasse and filter cake are the main residues of cane industrialization. Vinasse, which has potassium, calcium, and organic matter as main constituents, is generally used for regrowth fertilizations and may, as discussed above, provide all the K for cultivation. According to the origin of the vinasse, the concentrations of the elements may vary, and chemical analyses must be conducted before its application. However, in general, the concentration of K in the vinasse originating from mixed must is, on average, twice as higher as that obtained from broth, with values ranging from 2.5 and 1.2 kg m^{-3}, respectively.

Filter cake has a high percentage of moisture (approximately 75%), and average levels of P and Ca vary, respectively, from 5.0 to 10 and from 15 to 36 kg per ton of dry matter. It is used mainly in plant cane fertilization, applied at the bottom of the planting groove at an average dose of 30 t of natural matter per ha, or in total area at twice the dose. Considering an application of 40 t of natural filter cake per ha, around 10 t dry matter, with an average content of 7.0 kg of P per t of dry matter, there is a contribution of 70 kg of P per ha, dispensing phosphate fertilization at the time of planting for most soils.

The composting of organic residues, mainly of sugarcane bagasse, is one more option for the use of such residues in the fertilization of sugarcane and in the improvement of the physical and chemical properties of the soil. The authors evaluated the technical and economic feasibility of using organic compounds based on sugarcane bagasse in sugarcane plantation. The research was conducted in soils with a great physical heterogeneity and a high capacity of phosphorus adsorption. Different mixtures of sugarcane bagasse and chicken litter were tested, ranging from 100 kg of bagasse to 80 kg of bagasse +20 kg of chicken litter, plus

Year	**DM (t ha^{-1})**	**Nutrient (kg ha^{-1})**						
		N	**P**	**K**	**Ca**	**Mg**	**S**	**C**
1996	13.9 a	64 a	6.6 a	66 a	25 a	13 a	9 a	6.255 a
1997	10.8 b	53 a	6.6 a	10 b	14	8 b	8 a	3.642 b

Year	**Structural carbohydrates (kg ha^{-1})**						
	Hemicellulose	**Cellulose**	**Lignin**	**Cell content**	**C/N**	**C/S**	**C/P**
1996	3.747 a	5.376 a	1.043 a	3.227 a	97 a	695 a	947 a
1997	943 b	5.619 a	1.053 a	2.961 b	68 b	455 b	552 b

Source: Oliveira et al. [22]. Values followed by the same letter are not significantly different (Tukey's test) at the 0.05 level.

Table 12. Mass of dry matter (DM), amount of nutrients and structural carbohydrates in the samples of freshly harvested sugarcane straw without burning (1996) and in the remaining straw 1 year later (1997).

5.0 kg of ammonium sulfate. After the composting process, 15 t of material per hectare were applied to the bottom of sugarcane planting grooves. The fertilizer 06-30-24 was distributed over the compound at a dose of 500 kg per hectare. The results showed that the compound presenting the greatest productivity was the mixture of 100 kg of bagasse +5.0 kg of ammonium sulfate, resulting in an increase of 55 tons of culms per hectare compared to the treatment that received only chemical fertilization. The cost of production and the application of the compound were equivalent to 23.5 tons of culms, and the use of this compound allowed a net gain of 31.5 tons of culms per hectare. The results obtained in this study showed that even though sugarcane bagasse is a nutrient-poor residue, its effect on soil physical properties, especially aeration and water retention capacity, resulted in a higher productivity increase than that verified for compounds richer in nutrients. However, it also mineralized faster.

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