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Liming, fertilization and nutrition of star fruit trees: Review

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Abstract - Star fruit is an exotic fruit, originally from the topical regions of Asia, which found in Brazil adequate climatic conditions for its development, making it a promising species for cultivation throughout the country. However, despite the favorable climate, soils in tropical regions are generally acidic and have low natural fertility. In addition, due to the perennial condition of the star fruit tree, its roots remain for several years exploring practically the same soil volume, which requires constant monitoring of soil fertility and the nutritional status of plants. Research results have proven that the star fruit tree is responsive to liming and fertilizer application, with productivity gains and improvements in fruit quality. However, to ensure positive responses and success in agricultural activity, it is necessary that soil acidity correctors and fertilizers are applied in a technical and efficient manner based on the use of well-established agronomic tools, such as soil and leaf analysis. This review aims to gather information from studies, mainly those carried out in Brazil, on the nutritional requirements of star fruit trees, suggesting the best agronomic practices of soil fertility and nutrition of this fruit tree.

Index terms: *Averrhoa carambola*, soil acidity, fertilization, nutritional diagnosis, foliar analysis, soil fertility management.

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Calagem, adubação e nutrição da caramboleira: Revisão

Resumo - A caramboleira é uma frutífera exótica, originária das regiões topicais da Ásia, que encontrou no Brasil condições climáticas adequadas ao seu desenvolvimento, tornando-se uma espécie promissora para o cultivo em todo o País. Entretanto, apesar do clima favorável, nas regiões tropicais, os solos, em geral, são ácidos e de baixa fertilidade natural. Soma-se a isso, o fato de que, devido à condição perene da caramboleira, suas raízes permanecem por vários anos explorando praticamente o mesmo volume de solo, o que requer o monitoramento constate da fertilidade do solo e do estado nutricional das plantas. Os resultados de pesquisas têm comprovado que a caramboleira é responsiva à calagem e à aplicação de fertilizantes, com ganhos de produtividade e com melhorias na qualidade dos frutos. Entretanto, para garantir respostas positivas e sucesso na atividade agrícola, é necessário que os corretivos da acidez do solo e os adubos sejam aplicados de forma técnica e eficiente, com base no uso de ferramentas agronômicas já consagradas, como a análise de solo e de folhas. Esta revisão tem como objetivo reunir informações de pesquisas, principalmente as realizadas no Brasil, sobre as exigências nutricionais da caramboleira, sugerindo as melhores práticas agronômicas na área de fertilidade do solo e de nutrição dessa frutífera.

Termos para indexação: *Averrhoa carambola*, acidez do solo, fertilização, diagnose nutricional, análise foliar, manejo da fertilidade do solo.

Introduction

Star fruit tree (*Averrhoa carambola* L.) is a fruit tree belonging to the *Oxalidaceae* family, native to Southeastern Asia. It is widely distributed in many warm tropical and subtropical regions of the world, having been introduced in Brazil in the early 18th century (LENNOX; RAGOONATH, 1990; NAKASONE; PAULL, 1998). Taiwan, Malaysia, Brazil, Guyana, India, Philippines, Australia, Israel and the United States are among the main producing countries of this fruit (PAULL; DUARTE, 2012).

Star fruit is an exotic species with great agricultural potential, which found favorable climatic conditions in Brazil for full development. In 2017, the area harvested with this activity was estimated at 424 ha, whose orchards were distributed mainly in the Southeastern region of the country, with emphasis on the state of São Paulo, the largest national star fruit producer (IBGE, 2022).

Star fruit trees have rapid growth, development and high productivity. Depending on plant age and crop management, productivity varies between 15 and 45 t ha^{-1}, reaching up to 60 t ha^{-1} (BASTOS, 2004). In addition, fruits meet the main characteristics desired by consumers, such as flavor, aroma, color and nutritional properties, also standing out for their exotic beauty, which makes them very attractive.

The establishment of highly productive star fruit orchards requires the adoption of high-quality seedlings, that is, healthy and well-nourished. In this sense, the use of properly nourished seedlings is one of the primary factors that determines the success in the implementation of the star fruit orchard, which can affect production precocity, reflecting in the economic return on the capital invested by the producer (FREITAS et al., 2011; ROZANE et al., 2011a; ROZANE et al., 2013). It is known that poor nutrition of rootstocks and seedlings negatively reflects on the performance of plants in the field, resulting in poorly formed orchards, compromising the crop exploitation and the entire production process (NATALE et al., 2018).

Star fruit trees, as well as fruit trees in general, require different soil fertility and plant nutrition management, in relation to what is used in annual crops. Due to their perennial condition, fruit trees are explored in the long-term, with a thriving and comprehensive root system, which explores deeper soil layers, about which very little is known about available nutrient reserves and their contribution to fruit nutrition. Due to their arboreal size, this group of plants accumulates large amounts of nutrients in their organs, which can be remobilized in times of greater demand, in addition to presenting high nutrient exports through harvest.

The main areas of star fruit cultivation in Brazil are established in tropical soils, whose main characteristics are high acidity and low natural fertility. In these areas, the success of the fruit growing activity depends on the application of correctives and fertilizers, which must be applied in a technical and economic way, based on already established agronomic tools, such as chemical analyses of soil and leaves, allowing combining productivity, fruit quality and less environmental impact.

Studies carried out in areas of star fruit production in the state of São Paulo, the main fruit producer, has shown that the culture is responsive to soil acidity correction and fertilizer application, with satisfactory results in improving soil fertility and plant nutrition, resulting in better growth, gains in productivity and improvement in fruit quality (PRADO et al., 2005; LEAL et al., 2007; PRADO et al., 2007; NATALE et al., 2008; HERNANDES et al., 2008; HERNANDES et al., 2010a). Given these results and the promising condition of star fruit growing activity in Brazil, studies should aim at developing prediction models that are efficient in diagnosing soil fertility and plant nutrition, allowing for higher yields and higher quality fruits, with greater efficiency in the use of correctives and fertilizers applied in the orchard.

Due to the growing importance of this fruit in Brazil and the increase in production areas to meet market demand, the aim of this review was to present the available results of studies carried out on fertilization and nutrition of rootstocks and seedlings, liming, fertilization and orchard nutrition, as well as criteria for the diagnosis of soil fertility and plant nutritional status. In addition, doses, times and modes of application of correctives and fertilizers are suggested for the star fruit cultivation in the country, considering the real needs of the crop.

Seedling fertilization and nutrition

Fertilization and nutrition of seedlings of fruit species have not received the deserved attention in studies. This fact is confirmed by the scarcity of information in literature regarding adequate doses, sources, application times, splitting, diagnostic leaf, adequate leaf contents, etc., for rootstocks and seedlings of different species (NATALE et al., 2018). However, proper nutritional management of rootstocks and seedlings is essential to ensure satisfactory growth and development of any fruit species.

Star fruit seedlings, as well as any plant species, require nutrients in adequate amounts and proportions to ensure satisfactory growth and adequate nutritional status. It is important to point out that, when well nourished, rootstocks and seedlings can be better able to withstand adversities after transplanting, guaranteeing them greater survival in the field.

Fertilization of rootstocks and seedlings must be defined based on the nutritional requirements of each species, taking into account the absorption rate and nutrient accumulation over time. Aiming to evaluate the growth and nutrient accumulation by star fruit rootstocks (Malásia cultivar), grown in tubes (120 days) and transplanted into nutrient solution, Rozane et al. (2013) observed slow initial growth of rootstocks up to 50 days after transplanting (DAT), with higher nutritional requirements at 25 - 75 DAT and higher relative growth rate at 50 - 75 DAT, characterized by great stem, leaf and root development. It was also found that at 97 - 106 DAT, rootstocks accumulated 50% of the dry matter and nutrient mass.

In a similar study, Freitas et al. (2011) evaluated the growth and nutrient absorption rate in star fruit seedlings (Nota 10 cultivar), and found that at 82 - 126 DAT, the plant accumulated half of the total dry matter mass, with the highest nutritional requirement at 90 - 150 DAT. In seedlings of ‘B-10’ and ‘Golden Star’ cultivars, the highest growth rate and the highest dry matter accumulation occurred between 208 - 233 and 233 - 258 DAT, respectively (ROZANE et al., 2011a), with higher nutritional requirements at 208 - 233 DAT for ‘B-10’ and 233 - 283 DAT for ‘Golden Star’ cultivars (ROZANE et al., 2011b). Based on these results, N and K doses should be divided into at least four applications, the first being performed when transplanting the rootstock to the plastic bag and the others every 25 - 30 days.

For ‘Malásia’ rootstocks, the decreasing accumulation of nutrients at 125 DAT was (in mg plant^{-1}): N (634), K (368), Ca (152), Mg (106), S (98), P (88), (in µg plant^{-1}): Fe (2,963), Mn (2,165), Zn (780), B (722), Cu (96), with average accumulation in leaves > stem > roots (ROZANE et al., 2013). In ‘B-10’ and ‘Golden Star’ seedlings at 308 DAT, the accumulation was (in mg plant^{-1}): N (1,423 and 1,378), K (943 and 913), Ca (447 and 430), Mg (243 and 241), S (166 and 175), P (163 and 177), (in µg plant^{-1}): Fe (11,878 and 12,544), Mn (3,622 and 3,680), B (1,981 and 1,885), Cu (1,593 and 1,431) and Zn (1,409 and 1,349) (ROZANE et al., 2011b). In ‘Nota 10’ seedlings at 150 DAT, nutrient accumulation was (in mg plant^{-1}): N (1,058), K (871), Ca (347), P (159), S (147), Mg (123), (in µg plant^{-1}): Fe (28,071), Mn (5,850), Zn (2,271), B (1,753), and Cu (616) (FREITAS et al., 2011). The results of nutrient accumulation contribute to guide the doses of fertilizers to be applied in nurseries for the production of star fruit seedlings. However, it is worth remembering the importance of considering the efficiency of use of applied fertilizers.

The fertilization of star fruit seedlings, as well as of other fruit trees, is performed in an imprecise or empirical way, with lack of research in this regard (NATALE et al., 2018). Evaluating phosphate fertilization in 120-day-old star fruit seedlings grown in soil, Vitorazi Filho et al. (2017) observed that the maximum growth was obtained with doses of 143.8 mg kg^{-1} of P and for the basic fertilization of seedling growth, 20 mg kg^{-1} of N and 120 mg kg^{-1} of KCl were applied.

In the case of micronutrients, fertilization with doses of 3.8 mg dm^{-3} of Zn is recommended for star fruit rootstocks (LIMA NETO et al., 2015) and doses of 1.9 to 2.3 mg dm^{-3} of B, which provided higher nutrient levels and accumulation (XAVIER; NATALE, 2017). It is important to emphasize that caution is necessary, as there is a narrow limit between micronutrient deficiency and toxicity, and that high doses cause damage to seedlings due to competition and reduction in the translocation of some nutrients from roots to shoots (LIMA NETO; NATALE, 2014; LIMA NETO et al., 2015).

Nutritional status assessment is an important tool to follow the fertilization program of any fruit tree. For rootstocks and star fruit seedlings, there are no studies indicating the ideal sampling time, the diagnostic leaf, ranges of suitable levels, etc. Due to the lack of information and the difficulty in obtaining it, the ranges of leaf contents established in rootstocks and star fruit seedlings cultivated in nutrient solution are presented (Table 1), which can serve as a reference for nurserymen until their full definition. However, under these conditions, the ready and abundant supply of nutrients, as well as the higher concentration in relation to the soil solution, can result in higher levels in plants (ROZANE et al., 2011c).

Table 1. Contents of nutrients in rootstocks and star fruit seedlings grown in nutrient solution.

N	P	K	Ca	Mg	S
g kg^{-1}					
30.0 - 33.2 [(1)]	2.6 - 3.1	24.7 - 33.7	12.5 - 15.1	4.2 - 5.9	3.1 - 4.0
20.0 - 23.0 [(2)]	1.5	20 - 23	6.4 - 6.9	2.7 - 3.2	2.1 - 2.3

B	Cu	Fe	Mn	Zn
mg kg^{-1}				
69 - 81 [(1)]	3 - 4	116 - 144	266 - 433	35 - 46
46 - 55 [(2)]	2	35 - 45	74	27 - 30

Source: [(1)] Rozane et al. (2011c) - foliar contents for 'Malásia' star fruit rootstocks established based on the variation of contents obtained in each nutrient solution; [(2)] Hernandes et al. (2010) - foliar contents for star fruit seedlings 'BR96' cultivar. For Mn, dose of 0.5 mg L^{-1} (standard dose) was considered.

Soil chemical analysis and interpretation

Chemical analysis is the most adequate and reliable way to assess soil fertility, and consists of quantifying, through the use of analytical procedures, the level of nutrients found in available forms in the soil, as well as assessing the soil's ability to meet the nutritional requirements of plants. This technique is also the main tool used to establish corrective and fertilizer recommendations for fruit trees.

Among the several steps that make up the chemical analysis, sampling is the most sensitive and subject to errors, and must be properly performed, based on statistical criteria to minimize errors. When sampling is not properly performed, it does not represent the area to be evaluated and, as a consequence, recommendations for correctives and fertilizers are underestimated or overestimated, causing losses to the producer, who acquires inputs that plants do not need and/or reduced productivity, caused by lack or excess of nutrients. It is also worth remembering that errors made during sampling are not corrected in subsequent steps.

Before implementing the orchard, soil sampling for fertility assessment must follow the same criteria used for annual crops. Homogeneous areas should be sampled in terms of color, texture, slope, covering them in a zigzag pattern, randomly collecting at least 14 simple samples to compose the composite sample for each homogeneous area (HERNANDES et al., 2011a). In already established orchards, sampling should be carried out annually or at each end of the production cycle, and the most suitable period is after fruit harvest, at the end of the season. It is recommended to collect 14 and 17 simple samples in each plot to constitute a composite sample, in the 0-20 cm and 20-40 cm layers, respectively (considering sampling error of 20% acceptable), using the survey carried out by Hernandes et al. (2011a) in an eight-year-old star fruit orchard in the state of São Paulo as a reference.

In orchards in production, the soil layer to be sampled is 0-20 cm, whose results must be used to recommend fertilization and, eventually, liming. However, since fruit tree roots explore soil layers beyond the surface layer (0-20 cm), it is important to sample the 20-40 cm layer, in order to diagnose, especially, potential chemical limitations (calcium deficiency and/or excess aluminum) that prevent roots from deepening, as well as the continued verification of possible nutrient leaching.

It is noteworthy that the soil of the planting row must be sampled and interpreted separately from the soil between rows, because, due to the application of fertilizers for several years in strips on both sides of the plants (or in a circle around the fruit tree), differentiation will naturally occur in terms of fertility in the row (canopy projection), compared to fertility between rows (NATALE et al., 2008).

Soil sampling in the planting row must be carried out in the middle of the fertilized strip, coinciding with the canopy projection, whose results will guide recommendations for fertilizers and correctives, if necessary. On the other hand, sampling between rows should be carried out in the middle of the row, and results should be used to neutralize acidity, since studies have shown that the roots of fruit trees search for calcium and magnesium between rows, when these elements are depleted in the canopy projection (QUAGGIO, 2000; NATALE et al., 2007). Assuming that the soil may have high acidity and will need liming, sampling must be carried out in advance, allowing enough time to send samples to the laboratory, receiving of analysis results, limestone application and its effect on soil acidity correction, before the first subsequent fertilization.

Soil fertility interpretation is performed by comparing the results of chemical analyses with standard values, previously established and presented in recommended interpretation tables according to the analytical method used in laboratories, with variations in different Brazilian regions. This is due to the capacity of each extractor solution, and is a function of interactions with the soil, with the climatic condition, with the type of crop and/or management used.

To interpret soil fertility in fruit orchards, the classes of phosphorus and potassium availability in soils in the state of São Paulo are presented below (Table 2) (CANTARELLA et al., 2022), which stands out as the largest star fruit producer, where several studies have been conducted, which results are reported in this review. The interpretation classes for micronutrients in soils in the state of São Paulo are also presented (Table 3).

The interpretation of soil analyses allows diagnosing nutrient deficiencies/excesses, acidity, aluminum toxicity, etc., and, based on results, establishing management practices to adapt the soil to the plant to be cultivated. This diagnosis is extremely important for fruit growers, who generally apply standard amounts of fertilizers every year, regardless of soil fertility and/or plant nutritional status. However, it is important to point out that the nutritional requirements of plants vary from one place to another, mainly depending on soil and climate conditions, and determining levels in soil and leaves, through chemical analysis, is the first step to correct any deficiency or nutritional imbalance in the orchard.

Table 2. Interpretation classes of phosphorus and potassium concentrations, extracted with ion exchange resin in soils in the state of São Paulo.

Availability classes	Relative yield	P- resin (perennials)	K^+ exchangeable
	----------- % -----------	------ mg dm^{-3} ------	----- $mmol_c$ dm^{-3} -----
Very low	< 70	< 5	-
Low (1)	70 – 90	5 – 15	< 1.6
Medium	90 – 100	16 – 40	1.6 – 3.0
High	> 100	41 – 60	3.1 – 6.0
Very high (2)	> 100	> 60	> 6.0

Source: Cantarella et al. (2022). (1) There is no very low class for potassium and low class comprises relative yield less than 90%; (2) For phosphorus, by definition, the very high concentration class starts at twice the threshold of the high concentration class.

Table 3. Interpretation classes of micronutrient availability in soils in the state of São Paulo.

Availability classes	B	Cu	Fe	Mn	Zn
	(Hot water)	DTPA - TEA			
	mg dm^{-3}				
Low	< 0.6	< 2.0	< 5.0	< 5.0	< 5.0
Medium	0.6 – 1.0	2.0 – 5.0	5.0 – 12.0	5.0 – 10.0	5.0 – 10.0
High	> 1.0	> 5.0	> 12.0	> 10.0	> 10.0

Source: Cantarella et al. (2022)

Foliar diagnosis

Soil analysis, despite being a consolidated tool in agriculture, has some limitations. It should be noted that fertile soil, by itself, is not a guarantee of well-nourished and productive plants, since factors such as soil compaction, interaction among nutrients, water availability in the environment, etc., can compromise the absorption of essential elements. The last condition was observed by Rozane et al. (2022), when evaluating the nutrient uptake by two star fruit cultivars (B-10 and Golden Star), with approximately two years of age, under two water regimes (with and without irrigation). The authors concluded that, regardless of cultivar, the greatest nutrient uptake occurred in the irrigated regime. Thus, for most fruit trees, in addition to knowing soil fertility, there is a need to carry out leaf analysis due to perenniality, since this group of plants acquires a certain nutritional stability in the adult phase (MARSCHNER, 1995).

Leaf diagnosis is a method of evaluating the nutritional status of crops in which the diagnostic leaf or index leaf is analyzed at defined periods of the plant's life (NATALE; ROZANE, 2018). This important tool evaluates and calibrates the result of fertilization carried out based on soil analysis interpretation, in addition to being used to establish recommendations of nitrogen fertilization in several fruit trees, such as star fruit.

It should also be noted that the choice of the diagnostic leaf as the plant organ to be analyzed is based on the assumption that this is the key organ in the production of plant living matter, responsible for carbon assimilation, which presents more intense physiological activity and which expresses with greater sensitivity the availability of nutrients and, consequently, the productive capacity of the plant.

Leaf diagnosis is composed of several steps, with leaf sampling being the most critical and error-prone step, and leaves must be rigorously collected. Due to the great variation that can occur when analyzing plant tissues, the sample must be collected with the maximum possible homogeneity in terms of age, collection time, position in the branch and, in homogeneous orchards in terms of cultivar/variety, soil type, area management, plant health, productivity, climatic conditions, etc. It is not an exaggeration to stress the importance of collecting the correct leaf, at the adequate time and quantity, defined by previous studies.

The ideal leaf and the appropriate time to assess the nutritional status of star fruit trees were defined in research conducted by Prado and Natale (2004), who recommend that leaf sampling in star fruit orchards should be performed by collecting the 6th leaf with petiole, from the end of the branch (Figure 1), at about 1.5 m from the ground, in number of four leaves per tree, one in each cardinal point, in 25 plants per homogeneous plot, collected at full flowering.

It is important to emphasize that the leaves of star fruit trees are of the composite type, that is, they have a blade divided into small portions called leaflets (Figure 1). In a later study, Hernandes et al. (2011a) suggest sampling 20 plants in a homogeneous orchard, which would be sufficient for foliar macronutrient determinations. For micronutrients, at least 50 plants would be sampled (sampling error of 10% is considered acceptable).

After collection, leaf samples should be packed in identified paper bags and sent to the laboratory for analysis as soon as possible. If it is not possible to forward samples on the same day, they must be stored in refrigerator at temperature of around 5 °C until forwarding, which must take place within two days after collection in the field. Results must be interpreted so that management practices can be defined, if necessary, in order to maintain adequate plant nutrition, which will result in high yields.

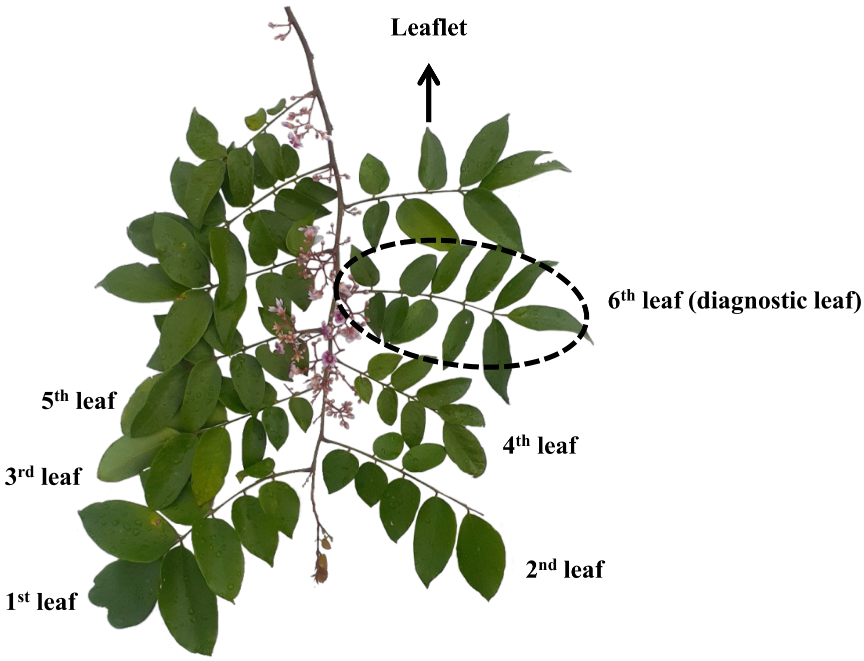

Figure 1. Star tree branch in full flowering, indicating the diagnostic leaf (6th leaf), to be sampled for the assessment of the nutritional status.

The assessment of the nutritional status of plants must be carried out by comparing the nutrient levels determined in each commercial plot with nutritional standards defined through studies, whenever possible, in the same region, with the same cultivar, soil and climate conditions and under similar crop management regime (ROZANE et al., 2015; NYOMBI, 2020).

Aiming at establishing preliminary nutritional norms for 'Nota 10' star fruit cultivar using the Composition Nutritional Diagnosis (CND) methodology, as indicated by Parent et al. (2013a,b), Rozane et al. (2015) and Rozane et al. (2020), 40 leaf samples were evaluated, as described in Hernandes et al. (2011a). According to the classification by Dancey and Reidy (2006), there is strong correlation (r = 0.82) between the nutritional imbalance index (CND-r^2) and the Mahalanobis distance (D^2) in the reference population (Figure 2), whose average production was 76 t ha^{-1}. It was observed that the greater the distance (D^2) of data in relation to the central tendency line, the greater the nutritional imbalance of plants (CND-r^2).

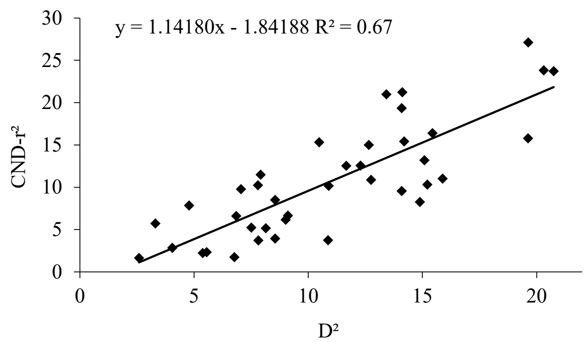

Figure 2. Relationship between nutritional imbalance index (CND-r^2) and the Mahalanobis distance (D^2) of the high-yield star fruit population.

The relationship between the CND index of each nutrient and its respective leaf content (Table 4) was adjusted using highly significant linear, quadratic or exponential models ($p < 0.0001$), whose determination coefficients (R^2) of models ranged from 0.59 to 0.87 for macronutrients and from 0.81 to 0.97 for micronutrients. In addition to the critical levels or equilibrium points, which correspond to the adequate levels of each nutrient in the leaf tissue, sufficiency ranges were also obtained (Table 4).

Table 4. Statistical models of the relationships between macronutrients (g kg-1) and micronutrients (mg kg-1) and the respective CND indices, as well as sufficiency ranges in leaf samples obtained by the CND method.

Nutrient	Equations (1)	R^2	Critical level (2)	Sufficiency range (3)
N	$y = 0.00049N - 10.77745^{**}$	0.59	22	21 - 23
P	$y = 0.00831P - 9.40641^{**}$	0.70	1.1	1.0 - 1.2
K	$y = 0.00058K - 8.36618^{**}$	0.74	14	13 - 15
Ca	$y = 5.7777\ln(Ca) - 54.297^{**}$	0.84	12	11 - 13
Mg	$y = 6.35854\ln(Mg) - 54.93196^{**}$	0.87	5.6	5.1 - 6.2
S	$y = 7.87799\ln(S) - 57.42576^{**}$	0.67	1.5	1.4 - 1.6
B	$y = 6.57341\ln(B) - 21.43124^{**}$	0.81	26	24 - 28
Cu	$y = 3.61772\ln(Cu) - 5.27874^{**}$	0.96	4	3 - 5
Fe	$y = -0.00046Fe^2 + 0.13863Fe - 6.13646^{**}$	0.92	54	46 - 62
Mn	$y = -0.00001Mn^2 + 0.01329Mn - 4.05421^{**}$	0.97	384	288 - 479
Zn	$y = -0.00596\,Zn^2 + 0.50316Zn - 7.91708^{**}$	0.91	21	18 - 24

(**) significant at 1% for the constant variance test and Kolmogorov-Smirnov; (1) Statistical model of regression analysis, relating nutrient contents with their respective indices; (2) Critical levels, or adequate content, obtained by assigning null value to the indices of equations of each nutrient; (3) Normal ranges obtained by equations equal to zero ± 2/3 of the standard deviation of contents of each nutrient.

Regarding star fruit tree nutrition, the high levels of manganese in leaves (Table 4) stand out, when compared to other micronutrients in the plant and also to the Mn determined in other fruit trees. These values are not just a result of the high Mn availability in the soil, either due to the source material or acidity that increases its solubility, especially in deeper soil layers. It is also a characteristic of star fruit trees, which absorb high amounts of manganese (HERNANDES et al., 2011a). There are several reports in literature indicating the participation of manganese in the synthesis of lignin, which stiffens tissues, increasing the physical barrier to the entry of pathogens, acting as a defense mechanism (MALAVOLTA et al., 1997). Hernandes et al. (2010b and 2011b) investigated the role of Mn in star fruit and concluded that most of the Mn present in leaves, stems and roots is strongly bound to tissues and therefore has active physiological function in plants.

Liming and gypsum

Among edaphic factors, acidity is one of the main chemical restrictions to plant growth and one of the causes that compromises crop productivity in tropical regions. In this sense, most Brazilian soils are naturally acidic, and are characterized by having low saturation by nutrient cations, such as Ca, Mg and K and, consequently, predominance of high H and Al concentrations linked to negative soil charges. This fact is due to the poverty in bases of rocks that gave rise to tropical soils and to climatic conditions, such as high temperature and precipitation, favorable to processes of intense weathering and leaching.

For fruit species, chemical restrictions caused by acidity can represent an even greater problem, since this group of plants remains for several years exploring the same soil volume, which is why liming is imperative, in order to precipitate toxic aluminum, raise pH and provide calcium and magnesium to plants (RAIJ, 2011). Thus, liming is the cheapest and fastest alternative to correct soil acidity, due to the relatively low price of this input, being the investment that brings the greatest economic return to producers. In fruit orchards, acidity correction in the surface and subsurface soil layers is essential to ensure the rapid establishment of plants in the field and fruit production precocity (BRUNETTO et al., 2020; CANTARELLA et al., 2022).

Despite the importance of correcting soil acidity for plant development, there are few studies evaluating the effects of liming on star fruit orchards. In the state of São Paulo, the largest star fruit producer in Brazil, Natale et al. (2008) conducted for seven consecutive years (1999 to 2006) a field experiment in a Typic Haplustox with the aim of establishing the most adequate base saturation for this crop. Increasing corrective doses were applied once in 1999, incorporated in the 0-30 cm layer, following the residual effect until 2006. At the end of the experimental period, the authors concluded that the highest accumulated fruit production was associated with pH of 4.6 and 5.0 and base saturation of 40 and 53%, respectively, in the row and between rows.

For the soil chemical attributes, it was found that, in addition to pH and base saturation, liming had significant and positive effects on the sum of bases and on the calcium and magnesium concentrations up to the 60 cm layer over time. The greater Ca and Mg availability in the soil, provided by limestone, was positively correlated with the foliar contents of these nutrients, with Ca = 7.6 g kg^{-1}, Mg = 4.0 g kg^{-1} and the Ca/Mg ratio = 1.9, which promoted the highest fruit production (NATALE et al., 2008).

The improvement of plant nutrition by Ca also provided greater fruit firmness due to its stabilizing function in the cell wall and, consequently, longer storage period (PRADO et al., 2005). In addition, Natale et al. (2011) demonstrated the economic feasibility of applying limestone which, due to its residual effect, is an important investment in perennial crops.

The best liming management strategy in the implementation of fruit orchards is to use coarse limestone (PRNT $<$ 60%), which has high residual effect, applied in the total area and incorporating into the soil 90 days before the planting of seedlings. In orchards in production, it is suggested to use fine limestone (PRNT $>$ 80%), applied to the surface without incorporation. In both the implantation and production phases, whenever the magnesium concentration in the soil is less than 9 $mmol_c$ dm^{-3}, limestone containing MgO concentration greater than 12% should be used due to the star fruit requirement (NATALE; ROZANE, 2018). It should be kept in mind that, over the years, there is a difference in soil fertility between row (shoot projection) and between rows, especially as a function of nitrogen fertilization. Thus, when necessary, liming must be carried out in the row, between rows or in the total area, depending on the result of the soil analysis.

Gypsum is a practice indicated for fruit trees, because this group of plants have a vigorous root system, which exploits large soil volume. This condition indicates that, in addition to evaluating the fertility of the surface soil layer (0-20 cm), the subsurface layer (20-40 cm) should also be sampled in order to evaluate the possible chemical impairments to roots.

Although there is no information in literature on gypsum in star fruit trees, it is suggested, based on Raij (2008), to apply gypsum when in the subsurface, the aluminum saturation (*m*) is greater than 40% and/or when the Ca concentration is less than 5.0 $mmol_c$ dm^{-3}, according to formula for calculating the gypsum requirement (GR), as follows: GR (kg ha^{-1}) = 6 x clay (g kg^{-1}). As an alternative to gypsum, simple superphosphate can be used when fertilizing with phosphorus. This is because this phosphate fertilizer has large amounts of gypsum in its composition, providing soil with calcium and sulfur and reducing aluminum saturation (*m*) in the subsurface (NATALE; ROZANE, 2018).

Pre-planting fertilization

Fertilization recommendations for fruit trees should be based on the interpretation of the results of chemical analyses of soil and leaves. For star fruit, the suggestion for pre-planting fertilization (Table 5) is based on results of long-term field studies carried out in orchards in the state of São Paulo (PRADO et al., 2005; PRADO et al., 2007; NATALE et al., 2008), which showed expressive responses of star fruit trees to the application of nutrients. The main aim of pre-planting fertilization is to stimulate root growth and provide the best settling of seedlings in the field.

Table 5. Dose of phosphate fertilizer indicated for the establishment of star fruit orchards based on the P concentration determined by soil analysis.

Interpretation classes	[(1)] P_2O_5 g per pit
Very low	180
Low	140
Medium	100
High	60

(1) Dose that can be linearly distributed within the planting furrow.

The doses of phosphate fertilizer to be supplied to star fruit trees in the pre-planting phase must consider the phosphorus concentrations available in the soil, determined by chemical analysis. Whenever possible, it is recommended to use granulated simple superphosphate or magnesium thermophosphate.

Pits of dimensions of 60 x 60 x 60 cm must be opened one month before planting in order to accommodate star fruit seedlings. Each pit must receive 20 L of tanned organic compost based on bovine manure, together with phosphate fertilizer doses (Table 5). Due to the constant poverty of tropical soils in some micronutrients, it is suggested to include in this phase 1.0 g of B (boric acid) and 2.0 g of Zn (zinc sulfate). These inputs (phosphorus, micronutrients and manure) must be mixed with the soil taken from the surface of the pit, using the mixture to fill the bottom of pits.

Phosphorus application should be carried out in the pit or in the planting furrow due to the low mobility of P in the soil profile. In the case of micronutrients, some fertilizer sources such as simple superphosphate and magnesium thermophosphate already contain boron and zinc in their composition, which facilitates the application of such small doses of these elements in the pit or planting furrow.

When the fruit grower chooses to plant seedlings in furrows, they must be about 50 cm deep and the mixture of inputs must be distributed along the entire furrow length. It is not recommended to apply acidity correctors in the pit or planting furrow, especially together with phosphate fertilizer, due to the reaction that can occur between phosphorus and calcium, forming tricalcium phosphate that precipitates, making P insoluble and unavailable to plants. For this reason, liming must be carried out in the total area 90 days prior to planting seedlings in the field.

Formation fertilization

Formation fertilization aims to stimulate the growth of the star fruit tree during its initial phase of adaptation in the field, ensuring more uniform orchards with less time to start production. The supply of fertilizers must be carried out after the setting of star fruit seedlings up to the age of three years, from when plants enter the full production phase. Recommendations were established based on soil analysis and plant age (Table 6).

Fertilizers should be annually applied around the canopy, in the range corresponding to the plant canopy projection, within a radius of 0.3 m from the trunk, increasing with age to 0.6 m, always in the canopy projection. It is recommended to divide, at least, in six applications spaced 30 days in the rainy season. Whenever possible, especially in sandy soils, use 25 liters per plant and per year of tanned organic compost based on bovine manure, or a third part in the case of poultry manure.

The recommendation of formation fertilization for star fruit (Table 6) is based on the results of long-term field studies with this

Table 6. Fertilization recommendation for star fruit trees in formation, according to soil analysis and plant age.

Age	Nitrogen	Phosphorus				Potassium			
		------- Interpretation classes -------				------- Interpretation classes -------			
		Very low	Low	Medium	High	Very low	Low	Medium	High
Years	N, g plant^{-1}	---------- P_2O_5, g plant^{-1} ----------				----------- K_2O, g plant^{-1} -----------			
0 – 1	50	0	0	0	0	100	80	50	30
1 – 2	100	100	50	30	0	200	150	100	50
2 – 3	200	150	100	60	0	400	300	150	80

When soil analysis shows B values lower than 0.21 mg dm^{-3} and Zn values lower than 0.8 mg dm^{-3}, 2.0 g plant^{-1} of B and 5.0 g plant^{-1} of Zn must be applied together with the formation fertilization.

fruit tree carried out in the state of São Paulo (PRADO et al., 2005; LEAL et al., 2007; PRADO et al., 2007; NATALE et al., 2008), which demonstrated significant responses of the crop to the application of nutrients.

Production fertilization

Production fertilization begins after the third year and aims to replace the amount of nutrients exported at the time of fruit harvest, as well as for the composition of dry matter in the formation of roots, branches and leaves. The doses are defined based on the expected productivity, soil fertility diagnosis and the nutritional status of plants (Table 7), and must be applied around the plant, in the canopy projection, within a radius of 0.6 m away from the trunk, without incorporation. Nitrogen and potassium fertilization should be divided, at least, into four equal portions.

The first application must be performed at the beginning of shoots, resulting from production pruning; the second must be performed in the full flowering; the third and fourth will be performed when fruits reach, respectively, about 2 cm and 4 - 5 cm in length.

Due to the sensitivity of the crop to the lack of Zn and B, it is recommended to apply, together with the production fertilization, 4.0 g plant^{-1} of Zn and 2.0 g of plant^{-1} of B, if the concentrations of these nutrients in the soil are very low or low (Table 3).

Table 7. Fertilization with N, P and K for star fruit orchard in production

Interpretation		Excepted fruit productivity (t ha^{-1})			
		< 30	30-50	50-80	> 80
Foliar N	**g kg^{-1}**	----------------------------- N, kg ha^{-1} year^{-1} ---------------------------------			
	< 21	141-200	201-250	251-300	301-350
	21-23	111-140	141-200	201-250	251-300
	> 23	80-110	111-140	141-200	201-250
P in soil		-------------------------------- P_2O_5, kg ha^{-1} year^{-1} ----------------------------			
	Very low	51-60	61-70	nv	nv
	Low	41-50	51-60	61-70	71-80
	Medium	31-40	41-50	51-60	61-70
	High	20-30	31-40	41-50	51-60
K no soil		--------------------------------- K_2O, kg ha^{-1} year^{-1} ----------------------------			
	Very low	111-140	141-180	nv	nv
	Low	81-110	111-140	141-180	181-220
	Medium	51-80	81-110	111-140	141-180
	High	30-50	51-80	81-110	111-140

nv – it is not feasible to achieve this production class with such low level of phosphorus or potassium in the soil.

Concluding remarks

The fruit growing activity has gained prominence in recent decades national and internationally due to the growing concern of the population in the search for foods that guarantee healthier and quality life, which includes fruits. If, on the one hand, fruit production should increase to meet the increasingly intense demand, on the other hand, it is necessary to use more advanced technologies that allow efficient yields and with the least possible environmental impact. One cannot think of more productive genetic materials without associating them with greater nutritional requirements, which implies the proper use of correctives and fertilizers, so that orchards can express their maximum productivity according to the soil and climate conditions. The star fruit tree found favorable conditions for its development in Brazil, and there is a great demand for tropical fruits by the consumer market. However, despite adequate climatic conditions, Brazilian soils generally present high acidity and low natural fertility, which, if not satisfactorily corrected, prevent star fruit from expressing its full productive potential. In view of the information reported in literature and presented in this review regarding fertilization and nutrition of fruit trees, it appears that the definition of the ideal base saturation for the crop, as well as fertilizer doses, combined with the establishment of nutritional standards, will allow producers the most efficient use of correctives and fertilizers, ensuring greater productivity and profitability. It should be emphasized; however, that the norms and recommendations were established for the cultivation conditions in the state of São Paulo. However, there is still a vast field of research to be explored, especially regarding the nutritional requirements of star fruit, and there is a need to improve crop management using soil analysis and foliar diagnosis to better understand the needs of the plant and, consequently, achieve greater fruit production with higher quality. Results of future research, seeking to respond to these and other aspects, should allow more rational recommendations of inputs, favoring the efficient management of orchards and preserving the environment.

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