Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil Fertility and Plant Nutrition

Diagnostic leaves for evaluating dwarf cashew nutritional status

Thais da Silva Martins[(1)], **Carlos Alberto Kenji Taniguchi**[(2)*], **Luiz Augusto Lopes Serrano**[(2)], **William Natale**[(3)], **Danilo Eduardo Rozane**[(4)] **and Adriana Guirado Artur**[(4)]

[(1)] Universidade Federal do Ceará, Departamento de Ciências do Solo, Fortaleza, Ceará, Brasil.
[(2)] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Agroindústria Tropical, Fortaleza, Ceará, Brasil.
[(3)] Universidade Estadual Paulista, Campus Experimental de Registro, Registro, São Paulo, Brasil.
[(4)] Universidade Federal do Ceará, Departamento de Fitotecnia, Fortaleza, Ceará, Brasil.

ABSTRACT: Cashew tree (*Anacardium occidentale* L.) is a fruit species widely cultivated in Brazil, but the interest in evaluating this plant nutritional status is very recent, to the point there is still no defined diagnostic leaf. This study aimed to define the leaves that reflect the nutritional status of dwarf cashews. Leaf samples were collected from a productive orchard established with four dwarf cashew clones: 'CCP 76', 'BRS 189', 'BRS 226', and 'BRS 265'. Leaf sampling was performed over four consecutive years, at the beginning of the flowering season and the emergence of inflorescences with floral buds. Sampling was carried out from the first to the sixth fully expanded (mature) leaf, from the inflorescence towards the base of the branch. Total leaf content of macronutrients, micronutrients, and Na were quantified. Multi-element index variables were obtained using Compositional Nutrient Diagnosis (CND) methodology, and total leaf concentrations were correlated with cashew nut yields. The pair of leaves closest to the base of the branch, 5th and 6th leaves, showed a balanced index of nutrients, including N, K, Ca, S, Mn, and Zn. These leaves were also positively correlated with cashew nut yield and exhibited lower coefficients of variation for most of the analyzed nutrients. Thereby, the 5th and 6th leaves are recommended as diagnostic leaves for evaluating the nutritional status of dwarf cashews.

Keywords: *Anacardium occidentale* L., CND, foliar diagnosis, nutrient concentrations.

*** Corresponding author:**
E-mail:
carlos.taniguchi@embrapa.br

Received: April 09, 2024

Approved: September 11, 2024

How to cite: Martins TS, Taniguchi CAK, Serrano LAL, Natale W, Rozane DE, Artur AG. Diagnostic leaves for evaluating dwarf cashew nutritional status. Rev Bras Cienc Solo. 2025;49:e0240080.
https://doi.org/10.36783/18069657rbcs20240080

Editors: José Miguel Reichert and Adelson Paulo de Araújo.

INTRODUCTION

The commercial species *Anacardium occidentale* L. is native to Brazil, but the cashew nut kernel is one of the most widely consumed nuts in the world, and in 2022 world exports amounted to almost US$ 7 billion. The largest producers of cashew nuts in the world in 2022 were Côte d'Ivoire (970,000 tons), India (752,000 tons) and Vietnam (341,000 tons). Brazil is the eighth largest producer, with 147,000 tons produced in 2022. Vietnam is the largest exporter worldwide, accounting for 42.4 % of the total exports, while the USA is the largest importer, with 14.7 % of the total (FAO, 2024).

Cashew has been commercially cultivated in Brazil since the 1960s, and currently, its cultivation covers 424,609 hectares, 98 % of which is in the northeast region (IBGE, 2022). Commercial cashew cultivation in Brazil started with common cashew trees grown from seeds that were the product of allogamy. This resulted in heterogeneous orchards that comprised plants differing from one another (Santos et al., 2020). Since the 1980s, short-sized clonal varieties termed dwarf cashews have been made available, which substantially increased the intensified cultivation of the crop. However, even with the availability of genotypes with improved genetic backgrounds, few orchards reach the full potential cashew nut yields (above >1,000 kg ha^{-1}), as shown in official data released by IBGE (2022) (≈347 kg ha^{-1}).

Plant nutritional status is extremely limiting among factors that interfere with crop yields. Several cashew producers fertilize their orchards by following the recommendations defined by Crisóstomo et al. (2009); however, there is no precise tool to evaluate the responses to fertilization or to diagnose the nutritional status of this crop. Plant analysis is important to elucidate in-season problems as deficiencies or excess of nutrients, thus complements soil testing (Zone et al., 2020). Leaves diagnosis technique allows for an indirect evaluation of soil fertility, using the plant as an extractor, since most physiological processes occur in the leaves. Evaluation of the nutritional status of plants allows producers to obtain greater economic returns, increase yield, and improve fruit quality (Rozane et al., 2016).

Of the steps to be followed for foliar diagnosis, leaf sampling is considered the most critical because, if performed incorrectly, it may misrepresent the actual nutritional status of the plant, so fertilization may be underestimated or overestimated, resulting in lower-than-expected crop yields (Oliveira et al., 2013). In addition, sampling criteria for each crop should be established because the leaf position on the branch is considered a source of variation for nutrient concentration; therefore, standardization is required to diagnose nutritional status to be effective (Lima et al., 2011).

Literature has previously reported leaf concentrations in cashews (Haag et al., 1975; Kernot, 1998), but these were obtained in common cashew orchards (heterogeneous plants). In addition, the samples were selected based on the criteria used for other fruit crops, and they were collected from various positions (Crisóstomo et al., 2004; Corrêa et al., 2012), thereby affecting the consistency of the information obtained.

Furthermore, several nutritional evaluation methods have been developed and researched since the mid-20th century, such as Critical Level, Sufficiency Range (univariate methods), Mathematical Chance (ChM), Diagnosis and Recommendation Integrated System (DRIS) (bivariate method), and Compositional Nutrient Diagnosis (CND) (multivariate method). The last-mentioned is based on the relationship between the concentration of a given nutrient and the geometric mean of the concentrations of other components in plant dry matter, thus using multivariate relationships (Parent and Dafir, 1992). This allows the calculation of an impartial imbalance index, that is, attributing the same weight imbalance to deficiencies and excesses, applying the Mahalanobis distance (Parent et al., 2009). The CND methodology has only one standard deviation, thus it allows the exclusion of atypical data (outliers) and increases its reliability in results interpretation.

Studies using this methodology for leaf diagnosis of crops are frequent in the literature, including orange (Camacho et al., 2012), mango (Politi et al., 2013; Wadt and Silva, 2020), guava (Oliveira et al., 2020), and grapevine (Rozane et al., 2020).

Considering the hypothesis that nutrient concentrations are influenced by the leaf position on the branch, this study aimed to define the leaves that reflect the nutritional status of dwarf cashews.

MATERIALS AND METHODS

The study was carried out in an orchard located in the Experimental Field of Embrapa Agroindústria Tropical, in Pacajus, Ceará, Brazil (4° 11' 19.63" S, 38° 30' 07.89" W, 84 m) (Figure 1), established in 2011 at a spacing of 8 × 6 m. The soil of the orchard is classified as Arenic Haplustults (*Argissolo Vermelho-Amarelo distrófico*) (Lima et al., 2002), and the climate of the region as "tropical, humid with a dry summer and rainy winter" according to Köppen classification system (Alvares et al., 2014). The studied orchard was established under rainfed conditions using four clones of dwarf cashew: 'CCP 76', 'BRS 189', 'BRS 226', and 'BRS 265', and distributed in a randomized complete block design with four replicates and 30 plants in each row. Plants of all clones were grafted onto dwarf cashew rootstock 'CCP 06', according to Serrano et al. (2013).

Before planting, the orchard area received 1.5 Mg ha^{-1} of dolomitic limestone (relative neutralizing value, RNV 90 %), which was incorporated into the soil by harrowing. Subsequently, the fertilizers single superphosphate (200 kg ha^{-1}) and FTE (fritted trace elements with 9 % Zn, 1.8 % B, 0.8 % Cu, 0.1 % Mo, 3 % Fe, and 2.0 % Mn, 20 kg ha^{-1}) were applied in planted furrows, and potassium chloride (20 kg ha^{-1}) and urea (20 kg ha^{-1}) were applied as top-dressings. In subsequent years, fertilization was always performed during the rainy season (February to April). Fertilization management was conducted based on soil analysis results and following the recommendations of Crisóstomo et al. (2009).

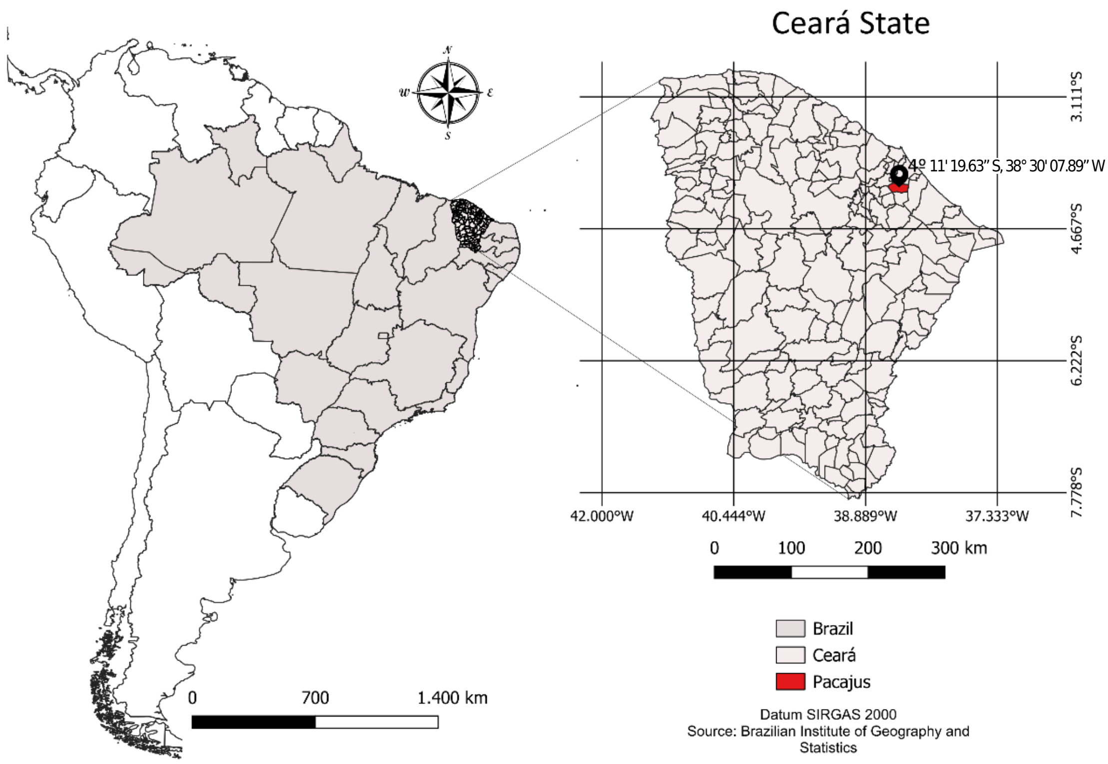

Figure 1. Map of the dwarf cashew leaf sampling in Pacajus, Ceará State, Brazil.

Leaf samples were collected at the beginning of the cashew flowering period (June to August, according to the specific phenology of each clone) in 2015, 2016, 2017, and 2018, corresponding to the 4th, 5th, 6th, and 7th years of cultivation, respectively. At the same time, soil samples were collected in the planting row and analyzed according to the methodology described by Silva et al. (2009) (Tables 1 and 2).

Leaves were collected from ten plants in each row of the orchard. Four branches (one per cardinal point) that had inflorescence (floral buds; Figure 2a) and located at heights from 1.5 to 1.8 m from the soil (Figure 2b) were selected. From each selected branch, leaves were collected from different positions: from the first to the sixth fully expanded leaf, and from the base of the inflorescence towards the branch base (Figure 2c). Each sample consisted of 40 leaves, i.e., four leaves per plant on ten plants. Each leaf position on the plant was made up of 64 samples, i.e., four clones, with four replicates collected over four years.

The collected leaves were placed in paper bags and taken to the Laboratory of Soil of Embrapa Agroindústria Tropical. Then, these leaves were washed in water, 3 % hydrochloric acid solution (v:v), and deionized water, placed in paper bags, and dried in a forced-air circulation oven at 65 °C until a constant weight was achieved. Subsequently, the samples were ground in a Wiley-type mill, passed through 1-mm mesh sieves, and stored in plastic containers with pressure caps.

The procedures described by Miyazawa et al. (2009) were used to conduct chemical analyses. Samples were subjected to sulfuric digestion, followed by distillation and titration to determine the total N concentration. Then, nitric-perchloric digestion was performed to obtain extracts and determine the P, K, Ca, Mg, S, Na, Cu, Fe, Mn, and Zn contents, using inductively coupled plasma optical emission spectrometry (ICP-OES). Samples were incinerated in a muffle furnace, followed by quantification by spectrophotometry using the azomethine-H method to determine B concentration. Sodium content was evaluated since it is important in semiarid and coastal regions, where Na accumulation can cause serious problems to soil and plants (Ehtaiwesh, 2022).

Table 1. Chemical analysis of the soil from the experimental area

Year	P	OM	pH(H_2O)	K^+	Ca^{2+}	Mg^{2+}	Na^+	H+Al	Al^{3+}	SB	CEC	BS
	mg dm^{-3}	g kg^{-1}		mmol$_c$ dm^{-3}								%
2015	11.3	4.8	6.7	0.9	11.0	7.0	3.0	10.0	0.0	21.0	31.0	69.0
2016	10.9	4.4	6.1	1.0	12.0	6.0	2.0	11.0	0.0	21.0	33.0	65.0
2017	11.7	4.6	5.6	1.2	14.0	4.0	0.0	16.0	0.0	20.0	36.0	55.0
2018	16.1	6.6	6.2	1.0	23.0	7.0	2.0	13.4	0.0	33.0	46.0	71.0

pH: soil:water ratio 1:2.5; OM: organic matter by Walkley-Black method; P, K^+ and Na^+: Mehlich-1 solution; Ca^{2+}, Mg^{2+} and Al^{3+}: 1 mol L^{-1} KCl solution; H+Al: $Ca(CH_3COO)_2.H_2O$ 0.5 mol L^{-1} solution; SB: Sum of Bases; CEC: Cation Exchange Capacity; BS: Base Saturation index.

Table 2. Chemical analysis of the soil in the experimental area

Year	Zn	Cu	Fe	Mn
	mg dm^{-3}			
2015	2.7	0.1	7.2	3.4
2016	1.6	0.1	4.9	3.8
2017	0.8	0.1	2.9	3.7
2018	1.6	0.2	9.7	11.5

Cu, Fe, Mn and Zn: Mehlich-1 extractor.

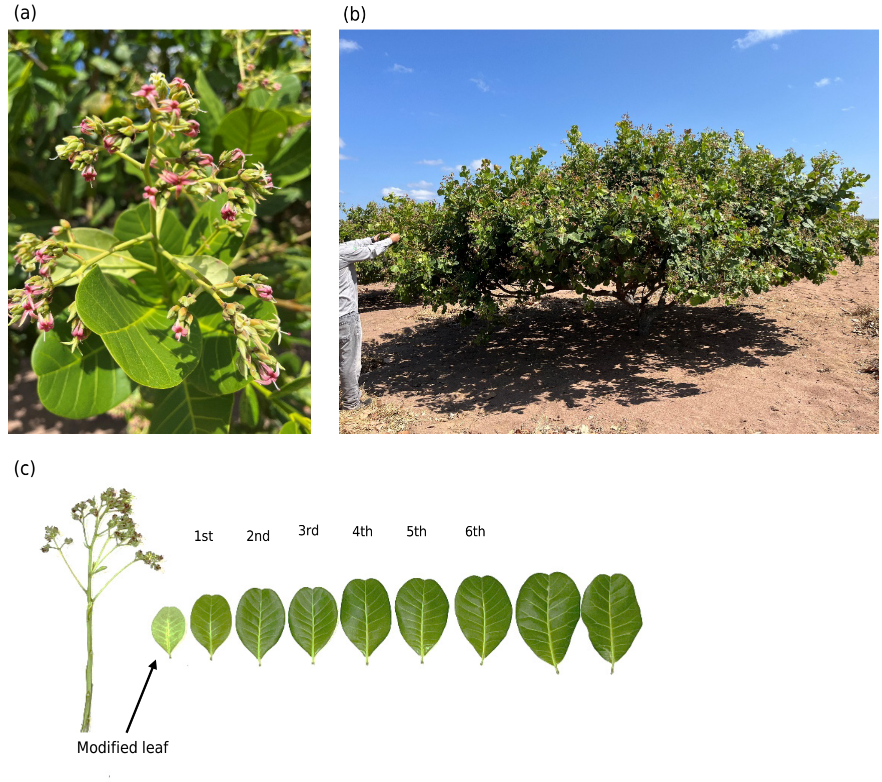

Figure 2. Floral buds (a), height on the plant (b) and leaf counting scheme (c) for assessing the nutritional status of dwarf cashew trees.

Cashew nuts were collected in the orchard during the fruiting period (August to December) in each year of evaluation. Nut yield (kg ha^{-1}) was calculated by weighing the cashew nuts after adjusting the moisture content to 8 %.

Three techniques were applied to define the diagnostic leaves. Pearson correlation coefficient and stepwise multiple linear regression (SAS Institute, 2018) were used to examine the relationship between nutrient and sodium concentrations in each mature leaf (1st, 2nd, 3rd, 4th, 5th, and 6th leaves) and in pairs (1st and 2nd, 2nd and 3rd, 3rd and 4th, 4th and 5th, and 5th and 6th leaves) with cashew nut yield. Alternatively, the balance index obtained with the methodology CND of the leaves, individually and in pairs, were also correlated with cashew nut yields. The CND standards were calculated from the cashew nut yield data and leaf nutrient and sodium contents. As indicated by Parent and Dafir (1992), the filling value (R) (Equation 1) was calculated and added to the proportions of the elements, corresponding to 100 % of the leaf dry matter.

$$R = 1000000 - \sum {}_{i=1}^{n} Nt_i \qquad \text{Eq. 1}$$

in which: R represents all components not determined in the dry matter (mg kg^{-1}); 1000000 represents the total dry matter amount (mg kg^{-1}); and Nt_i is the content of each nutrient in the dry matter, in mg kg^{-1}.

Then, geometric means (Equation 2) were calculated, including the concentrations of all nutrients, plus the R-value.

$$G = \left[\left(\prod {}_{i=1}^{n} Nt_i\right) \cdot R\right]^{\frac{1}{(n+1)}} \qquad \text{Eq. 2}$$

in which: G is the geometric mean of nutrient content in the dry matter; Nt_i is the content of each nutrient in the dry matter; R is the value of components not determined in the dry matter; and n is the number of nutrients analyzed.

To express each simple component in comparison with all the others, that is, in comparison with the geometric means of the observed values, multi-element variables (Equation 3) (Beverly, 1987) were calculated using the Napierian logarithm.

$$V_i = \ln\left(\frac{Nt_i}{G}\right) \quad \text{Eq. 3}$$

in which: V_i is the value of the multi-element variable; G is the geometric mean of nutritional concentration; and Nt_i is the concentration of each nutrient in the dry matter.

Before proceeding with the classification of the CND indices, using the calculation of the Mahalanobis distance (Equation 4), it was possible to identify and exclude outliers from the database, as this identifies the imbalance of elements present in the reference population.

$$D^2 = \sum{}_{i=1}^{n}\left(clr_i - \overline{clr_i}\right)^T \mathrm{COV}^{-1}\left(clr_i - \overline{clr_i}\right) \quad \text{Eq. 4}$$

in which: D^2 is the Mahalanobis distance; clr_i is the sample to be compared; $\overline{clr_i}$ is the arithmetic mean of the reference population; and *COV* is the covariance matrix of the reference population.

Based on D^2 to exclude plots that had a value <1 % probability ($p<0.01$), the χ^2 test was used. Then, the database was separated into a low-yielding population and a high-yielding population (reference population), based on the inflection point of the cubic function, fitted between the values of the accumulated function and D^2. The CND indices of the multi-element variables were calculated according to equation 5.

$$I_i = \frac{(V_i - \bar{V}_i)}{\sigma_i} \quad \text{Eq. 5}$$

in which: I_i is the balance index of nutrient *I* to determine *CND*; V_i is the value of the multi-element variable *I* of the evaluated samples; $\bar{V}_i$ is the average of the values of the multi-nutrient variable *I* in the reference population; and σ_i is the standard deviation of variable *I* in the reference population.

After obtaining the CND indices for each leaf evaluated, they were related to the yield through correlation analysis to indicate the diagnostic leaf with the highest correlation with cashew yield.

RESULTS AND DISCUSSION

The dwarf cashew database, composed of 64 samples, indicates variations in cashew nut yields from 358 to 2,193 kg ha^{-1} with a standard deviation of 434 kg ha^{-1}. Using the Mahalanobis distance allowed us to exclude 26 outliers from the database. Subsequently, the normal distribution of yields and the multivariate relationships of nutrients in the leaf samples were determined by observing the normal distribution of the variables using the Kolmogorov-Smirnov test.

Pearson correlation matrix was used primarily to assess the relationship between the levels of each nutrient and Na in isolated leaves (1st, 2nd, 3rd, 4th, 5th, and 6th) and in pairs (1st and 2nd, 2nd and 3rd, 3rd and 4th, 4th and 5th, and 5th and 6th) and the yield of dwarf cashew nuts. The elements that were related to nut yield were N, S, and Zn; however, they did not exhibit differences in relation to the leaf positions sampled alone or in pairs in the branches of dwarf cashew plants (Table 3). Negative correlations between N and S concentrations in the leaves and cashew nut yield may be related to the dilution effect reported by Jarrell and Beverly (1981), in which the nutrient uptake rate does not follow the increase in the growth rate. It should also be noted that dwarf cashew plants differ in size and that the fertilizer management was the same for all clones.

Table 3. Pearson correlation matrix between contents of nutrients and sodium in dwarf cashew leaves and cashew nut yield (Y), as a function of leaf position in the branch

Cashew nut yield	Leaf	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Na
Y	1st	**-0.54**	0.09	-0.02	-0.14	-0.18	**-0.52**	0.10	-0.07	-0.16	-0.03	**0.38**	-0.15
Y	2nd	**-0.41**	0.13	0.05	-0.08	-0.10	**-0.43**	0.03	0.05	-0.06	0.08	**0.27**	-0.13
Y	3rd	**-0.45**	0.15	0.08	0.05	0.05	**-0.38**	0.13	0.09	-0.08	0.13	**0.32**	-0.07
Y	4th	**-0.45**	0.09	-0.08	0.08	0.04	**-0.42**	0.11	0.01	-0.05	0.11	0.25	-0.08
Y	5th	**-0.50**	0.08	-0.10	0.18	0.09	**-0.48**	0.15	0.04	0.08	0.24	**0.39**	-0.10
Y	6th	**-0.51**	0.01	-0.21	0.23	0.09	**-0.48**	0.07	0.13	0.11	0.24	**0.36**	-0.05
Y	1st and 2nd	**-0.47**	0.11	0.01	-0.11	-0.14	**-0.47**	0.06	-0.01	-0.10	0.02	**0.32**	-0.14
Y	2nd and 3rd	**-0.43**	0.14	0.06	-0.02	-0.03	**-0.40**	0.08	0.07	-0.06	0.10	**0.29**	-0.10
Y	3rd and 4th	**-0.45**	0.12	0.00	0.06	0.05	**-0.40**	0.12	0.05	-0.06	0.12	**0.28**	-0.08
Y	4th and 5th	**-0.47**	0.09	-0.08	0.13	0.06	**-0.45**	0.13	0.02	0.02	**0.18**	**0.32**	-0.09
Y	5th and 6th	**-0.50**	0.05	-0.15	**0.20**	0.09	**-0.48**	0.11	0.09	0.10	**0.24**	**0.38**	-0.07

Bold values represent correlations significant at $p<0.05$.

For pairs of 4th and 5th and 5th and 6th leaves, the contents of Mn, Zn and Ca were also correlated with cashew nut yields, indicating that the collection of leaves in pairs is a better strategy than the collection of individual leaves for evaluating the nutritional status of dwarf cashew plants.

With a definition of suitable diagnostic leaves, the chances of errors regarding nutritional balance are lower; that is, the decreases in yield related to deficiency or excess of nutrients are smaller (Rozane et al., 2016), thus highlighting the importance of defining the correct leaves to be sampled.

Nut yield was related to a small number of elements, since, under field conditions, this variable is conditioned not only on the concentrations of particular elements in the leaves, but also on their relationship with other elements and biotic and abiotic factors that act simultaneously during plant development.

The multiple linear regressions between cashew nut yield and contents of nutrients and Na in pairs of leaves showed that the pair of 5th and 6th leaves was correlated with N, P, Ca, Mg, S and Na contents and had the highest fitting coefficients (R^2 and adjusted R^2) (Table 4). The estimated parameters of the regression (N, P, Ca and S contents) were significant at 1 % level, and Mg and Na contents were significant at 5 % level (Table 4) for sampling the pair of 5th and 6th leaves, possibly due to the nutrients use efficiencies of the dwarf cashew clones.

Analysis of the standardized residuals was used to evaluate the quality of fit of the model. The better fit occurred for the pair of 5th and 6th leaves, where the points were random and homogeneous around the horizontal axis with a value equal to zero (Draper and Smith, 1998). The highest simple linear correlation (r) between the estimated and observed values of dwarf cashew yield was also obtained for this pair of leaves (Figure 3).

When defining the diagnostic leaf, the relationship between yield and nutrient contents in leaf tissue should be considered, so that the assessment of plant nutritional status is efficient (Silva et al., 2018). However, it is not always possible to find a correlation with all nutrients (Oliveira et al., 2020). This is due to the fact that, especially under field conditions, yield is greatly influenced by interactions between nutrients and various other factors, such as light, CO_2 and water. The increase in the supply of any of these factors also causes increments in growth rate and yield. Another important aspect to consider is that plants have specific nutrient requirements and factors inherent to the plant itself, such as leaf area. In addition, two types of yield response are related to nutrient contents: it can be quantitative, that is, the yield itself, or qualitative, such as sugar and protein concentrations in the fruits (Marschner, 2012).

Using the vectorization of the multi-nutrient balance index, the 5th and 6th leaves were correlated with cashew nut yield for N, S, Mn, and Zn and N, K, S, Mn, and Zn, respectively (Table 5). Nitrogen, S, and Zn correlated with cashew nut yield, regardless of the position of the sampled leaf in the branch, and there was agreement between the uni- and multi-nutrient methods in this regard.

Multi-nutrient relationships identified by the CND method were more efficient in evaluating plant nutritional status than analyzing a single element as a limiting factor for crop growth and yield. In addition, even though the cashew clones are dwarf, there are differences between them in terms of plant size, and probably differences in terms of nutrient use efficiencies.

Considering the sampling of pairs of leaves, the vectorization of the multi-nutrient balance index of the 4th and 5th and 5th and 6th leaves was related to nut yields for N, S, Mn, and Zn and for N, K, Ca, S, Mn, and Zn, respectively.

Table 4. Parameters of multiple linear regression equations between contents of nutrients and sodium in dwarf cashew leaves and cashew nut yield, as a function of leaf position in the branch

Independent variable	Pair of leaves				
	1st and 2nd	2nd and 3rd	3rd and 4th	4th and 5th	5th and 6th
			Estimated parameter		
Intercept	2723.12**	1787.00**	2068.43**	2232.48**	2831.86**
N	-65.49**	-70.80**	-86.30**	-90.89**	-80.93**
P	454.21*	809.54**	808.60**	730.63**	732.48**
Ca			358.62**	393.88**	479.20**
Mg					-452.82*
S	-1266.79**	-993.11**	-1177.27**	-1190.02**	-1275.63**
Mn	4.86**	4.48**			
Na	-390.97*		-232.96*	-282.19*	-401.21*
F test	16.33**	17.41**	21.85**	22.75**	21.26**
R^2	0.401	0.362	0.428	0.483	0.513
R^2 adjusted	0.376	0.341	0.405	0.461	0.489

** and *: significant at p<0.01 and p<0.05, respectively.

Table 5. Pearson's correlation matrix between balance index of nutrients and sodium in dwarf cashew leaves and cashew nut yield (Y), as a function of leaf position in the branch

	Leaf	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Na
Y	1st	**-0.48**	0.13	0.05	-0.11	-0.11	**-0.43**	0.17	-0.02	-0.07	0.02	**0.40**	-0.11
Y	2nd	**-0.44**	0.11	0.03	-0.07	-0.11	**-0.44**	0.07	0.08	-0.05	0.11	**0.31**	-0.12
Y	3rd	**-0.54**	0.09	-0.01	0.01	-0.06	**-0.48**	0.11	0.09	-0.09	0.15	**0.33**	-0.12
Y	4th	**-0.47**	0.05	-0.10	0.10	0.01	**-0.49**	0.14	-0.03	-0.03	0.14	**0.27**	-0.11
Y	5th	**-0.58**	-0.03	-0.16	0.17	-0.05	**-0.53**	0.11	0.01	0.08	**0.25**	**0.29**	-0.15
Y	6th	**-0.58**	-0.13	**-0.29**	0.22	-0.08	**-0.55**	0.04	0.11	0.11	**0.25**	**0.31**	-0.13
Y	1st and 2nd	**-0.46**	0.12	0.04	-0.09	-0.11	**-0.44**	0.11	0.03	-0.06	0.06	**0.35**	-0.11
Y	2nd and 3rd	**-0.49**	0.10	0.01	-0.03	-0.08	**-0.46**	0.09	0.08	-0.07	0.13	**0.32**	-0.12
Y	3rd and 4th	**-0.51**	0.07	-0.05	0.05	-0.02	**-0.49**	0.13	0.03	-0.06	0.14	**0.30**	-0.11
Y	4th and 5th	**-0.53**	0.00	-0.14	0.13	-0.02	**-0.52**	0.13	-0.02	0.02	**0.20**	**0.30**	-0.13
Y	5th and 6th	**-0.58**	-0.08	**-0.23**	**0.19**	-0.07	**-0.54**	0.07	0.07	0.10	**0.25**	**0.30**	-0.13

Marked correlations are significant at p<0.05.

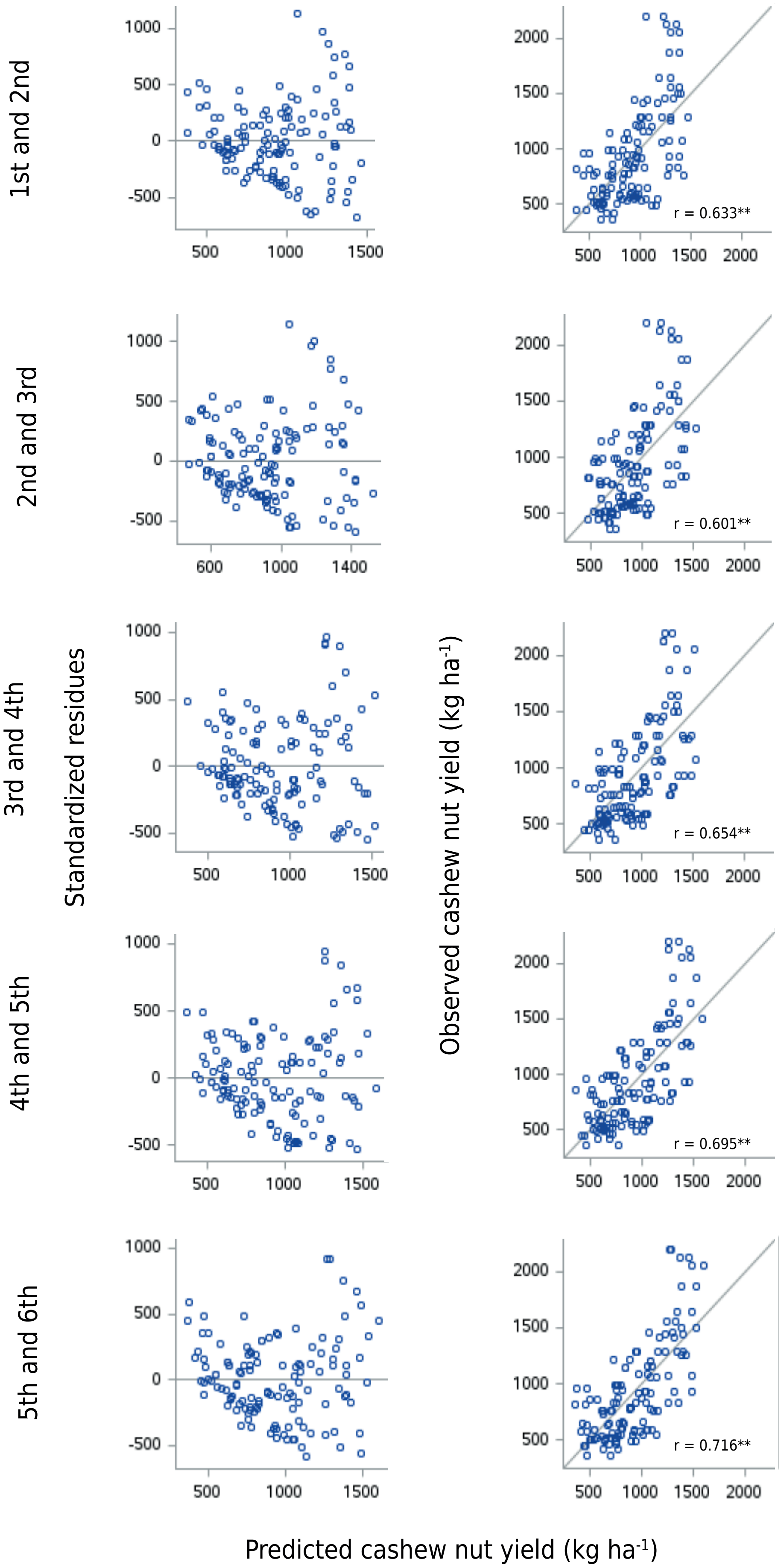

Figure 3. Standardized residues and observed cashew nut yield and predicted cashew nut yield.

Table 6. Coefficients of variation of nutrients and sodium in dwarf cashew leaves, as a function of leaf position in the branch

Elements	Pair of leaves				
	1st and 2nd	2nd and 3rd	3rd and 4th	4th and 5th	5th and 6th
	%				
N	8.97	8.68	7.99	7.89	7.93
P	15.80	15.76	15.71	14.12	12.97
K	9.41	9.62	10.39	8.89	7.23
Ca	21.17	21.58	21.15	19.81	19.29
Mg	10.43	10.41	10.76	10.34	9.67
S	6.91	8.33	9.16	8.04	6.75
B	23.78	23.61	20.72	21.53	24.14
Cu	20.21	17.56	19.43	18.91	20.94
Fe	37.46	40.58	35.51	30.15	29.99
Mn	30.97	31.53	31.87	29.28	26.90
Zn	21.93	20.32	17.90	16.62	18.85
Na	18.10	18.15	18.46	17.45	15.83

Sulfur, followed by N, showed the least variability in nutrient contents in all pairs of leaves sampled; Fe exhibited the greatest variability (Table 6). The pair of 5th and 6th leaves had the lowest coefficient of variation for most of the elements analyzed, with the exceptions of B, Cu, and Zn (Table 6), that is, greater stability and less randomness of leaf contents, thus being able to reflect better the nutritional status of plants (Wadt and Silva, 2016).

Multiple linear regression and the multi-nutrient balance index demonstrated similar and complementary correlations between nutrients and Na and the yield of dwarf cashews. Considering the two techniques in the pair of 5th and 6th leaves, N, P, K, Ca, Mg, S, Mn, Zn and Na were the elements that influenced yield.

Based on single and multi-element analyses and considering the yield of cashew nuts and the lowest coefficients of variation of the elements, the 5th and 6th leaves can be used as diagnostic leaves to evaluate the nutritional status of the dwarf cashew tree. These leaves in dwarf cashew plants are the ones that are closest to the base of the branch, thus being consistent with the indication that the diagnostic leaves are physiologically mature and with maximum photosynthetic activity, since they are a source of photoassimilates (Marschner, 2012).

The definition of the diagnostic leaf for dwarf cashew will allow the definition of the nutrient sufficiency range for the crop and the application of nutritional status assessment tools such as DRIS and CND. Using these tools to assess the nutritional status of dwarf cashew trees will allow farmers to adjust fertilizer recommendations, optimizing their use and reducing nutrient losses.

CONCLUSION

The pair of mature 5th and 6th leaves, from the inflorescence towards the base of the branch, collected at the beginning of flowering (flower buds) are the most suitable for determining the nutritional status of dwarf cashew trees.

DATA AVAILABILITY

All data was generated or analyzed in this study.

AUTHOR CONTRIBUTIONS

Conceptualization: Carlos Alberto Kenji Taniguchi (equal) and Luiz Augusto Lopes Serrano (equal).

Data curation: Carlos Alberto Kenji Taniguchi (equal), Luiz Augusto Lopes Serrano (equal) and Thais da Silva Martins (equal).

Formal analysis: Adriana Guirado Artur (equal), Carlos Alberto Kenji Taniguchi (equal), Danilo Eduardo Rozane (equal) and Thais da Silva Martins (equal),

Funding acquisition: Luiz Augusto Lopes Serrano (lead).

Investigation: Adriana Guirado Artur (equal), Carlos Alberto Kenji Taniguchi (equal), Luiz Augusto Lopes Serrano (equal) and Thais da Silva Martins (equal).

Methodology: Adriana Guirado Artur (supporting), Carlos Alberto Kenji Taniguchi (lead) and Luiz Augusto Lopes Serrano (supporting).

Project administration: Luiz Augusto Lopes Serrano (lead).

Resources: Carlos Alberto Kenji Taniguchi (lead) and Luiz Augusto Lopes Serrano (supporting).

Supervision: Adriana Guirado Artur (supporting), Carlos Alberto Kenji Taniguchi (lead) and Luiz Augusto Lopes Serrano (supporting).

Writing – original draft: Adriana Guirado Artur (equal), Carlos Alberto Kenji Taniguchi (equal), Thais da Silva Martins (equal) and William Natale (equal).

Writing – review & editing: Adriana Guirado Artur (equal), Carlos Alberto Kenji Taniguchi (equal), Danilo Eduardo Rozane (equal), Thais da Silva Martins (equal) and William Natale (equal).

REFERENCES

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. Köppen's climate classification map for Brazil. Meteorol Z. 2014;22:711-28. https://doi.org/10.1127/0941-2948/2013/0507

Beverly RB. Fertilizer use efficiency: modified DRIS method for simplified nutrient diagnosis of 'Valencia' oranges. J Plant Nutr. 1987;10:1401-8. https://doi.org/10.1080/01904168709363672

Camacho MA, Silveira MV, Camargo RA, Natale W. Faixas normais de nutrientes pelos métodos ChM, DRIS e CND e nível crítico pelo método de distribuição normal reduzida para laranjeira-pera. Rev Bras Cienc Solo. 2012;36:193-200. https://doi.org/10.1590/S0100-06832012000100020

Corrêa MCM, Queiroz RF, Ruppenthal V. Diagnose foliar nas culturas do caju e do caqui. In: Prado RM, editor. Nutrição de plantas: Diagnose foliar em frutíferas. Jaboticabal, SP: Funep; 2012. p. 381-410.

Crisóstomo LA, Pimentel CRM, Miranda FR, Oliveira VH. Cajueiro-anão precoce. In: Crisóstomo LA, Naumov A, editors. Adubando para alta produtividade e qualidade: Frutíferas tropicais do Brasil. Fortaleza, CE: Embrapa Agroindústria Tropical; Horgen, Suiça: International Potash Institute; 2009. p. 50-69.

Crisóstomo LA, Rossetti AG, Pimentel CRM, Barreto PD, Lima RN. Produtividade, atributos industriais e avaliação econômica de castanha em cajueiro-anão precoce adubado com doses crescentes de nitrogênio e potássio, em cultivo sob sequeiro. Rev Cienc Agron. 2004;35:87-95.

Draper NR, Smith H. Applied regression analysis. 3rd ed. New York: John Wiley & Sons, Inc.; 1998.

Ehtaiwesh AF. The effect of salinity on nutrient availability and uptake in crop plants. J Appl Sci. 2022;9:55-73. https://doi.org/10.47891/sabujas.v0i0.55-73

Food and Agriculture Organization of the United Nations - FAO. FAOStat: Crops and livestock products. Rome: FAO; 2024 [cited 2024 July 24]. Available from: https://www.fao.org/faostat/en/#data/QCL.

Haag HP, Sarruge JR, Oliveira GD, Dechen AR. Nutrição mineral do cajueiro (*Anacardium occidentale* L.). I – Deficiência dos macronutrientes – Nota prévia. An Esc Super Agric Luiz de Queiroz. 1975;32:185-90. https://doi.org/10.1590/S0071-12761975000100014

Instituto Brasileiro de Geografia e Estatística - IBGE. Produção agrícola municipal. Rio de Janeiro: IBGE; 2022 [cited 2023 July 27]. Available from: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9201-levantamento-sistematico-da-producao-agricola.html?=&t=resultados.

Jarrell WM, Beverly RB. The dilution effect in plant nutrition studies. Adv Agron. 1981;34:197-224. https://doi.org/10.1016/S0065-2113(08)60887-1

Kernot I. Cashew information kit. Queensland: Department of Primary Industries; 1998. (Series: Agrilink your growing guide to better farming).

Lima AAC, Oliveira FNS, Aquino ARL. Classificação e aptidão agrícola dos solos do campo experimental de Pacajus, Ceará, para a fruticultura. Fortaleza: Embrapa Agroindústria Tropical; 2002. (Documentos, 53).

Lima RLS, Severino LS, Cazetta JO, Azevedo CAV, Sofiatti V, Arrie NHC. Posição da folha e estádio fenológico do ramo para análise foliar do pinhão manso. Rev Bras Eng Agr Ambient. 2011;15:1068-72. https://doi.org/10.1590/S1415-43662011001000011

Marschner P. Marschner's mineral nutrition of higher plants. 3rd ed. San Diego, USA: Academic Press; 2012.

Miyazawa M, Pavan MA, Muraoka T, Carmo CAFS, Melo WJ. Análise química de tecido vegetal. In: Silva FC, editor. Manual de análises químicas de solos, plantas e fertilizantes. 2. ed. rev. e ampl. Brasília, DF: Embrapa; 2009. p. 191-234.

Oliveira CT, Rozane DE, Amorim DA, Souza HA, Fernandes BA, Natale W. Diagnosis of the nutritional status of 'Paluma' guava trees using leaf and flower analysis. Rev Bras Frutic. 2020;42:e-132. https://doi.org/10.1590/0100-29452020132

Oliveira VH, Taniguchi CAK, Crisóstomo LA. Nutrição mineral do cajueiro. Brasília, DF: Embrapa Agroindústria Tropical; 2013. (Documentos, 14).

Parent LE, Dafir M. A theoretical concept of compositional nutrient diagnosis. J Amer Soc Hort Sci. 1992;117:239-42.

Parent LE, Natale W, Ziadi N. Compositional nutrient diagnosis of corn using the Mahalanobis distance as nutrient imbalance index. Can J Soil Sci. 2009;89:383-90. https://doi.org/10.4141/cjss08050

Politi LS, Flores RA, Silva JAS, Wadt PGS, Pinto PAC, Prado RM. Estado nutricional de mangueiras determinado pelos métodos DRIS e CND. Rev Bras Eng Agr Ambient. 2013;17:11-8. https://doi.org/10.1590/S1415-43662013000100002

Rozane DE, Parent LE, Natale W. Evolution of the predictive criteria for the tropical fruit tree nutritional status. Científica. 2016;44:102-12. https://doi.org/10.15361/1984-529.2016v44n1p102-112

Rozane DE, Paula BV, Melo GWB, Santos EMH, Trentin E, Marcheza C, Silva LOS, Tassinari A, Dotto L, Oliveira FN, Natale W, Baldi E, Toselli M, Brunetto G. Compositional nutrient diagnosis (CND) applied to grapevines grown in subtropical climate region. Horticulturae. 2020;6:56. https://doi.org/10.3390/horticulturae6030056

Santos RM, Natale W, Taniguchi CAK, Corrêa MCM, Serrano LAL, Artur AG. Association of controlled-release and foliar fertilizers in the production of grafted dwarf cashew seedlings. J Plant Nutr. 2020;43:1048-56. https://doi.org/10.1080/01904167.2020.1711934

SAS Institute. SAS® Studio 5.1: User's Guide. Cary, NC: SAS Institute Inc.; 2018. Available from: https://documentation.sas.com/api/docsets/webeditorug/5.1/content/webeditorug.pdf?locale=en.

Serrano LAL, Melo DS, Taniguchi CAK, Vidal Neto FC, Cavalcante Júnior LF. Porta-enxertos para a produção de mudas de cajueiro. Pesq Agropec Bras. 2013;48:1237-45. https://doi.org/10.1590/S0100-204X2013000900007

Silva EB, Ferreira EA, Magalhães SC, Chaves CMMB, Duarte E, Farnezi MMM. Selection of index leaf for foliar diagnosis of critical nutrient levels in physic nut (*Jatropha curcas*). Aust J Crop Sci. 2018;12:1377-84. https://doi.org/10.21475/ajcs.18.12.09.PNE764

Silva FC, Abreu MF, Perez DV, Eira PA, Abreu CA, van Raij B, Gianello C, Coelho AM, Quaggio JA, Tedesco MJ, Silva CA, Barreto WO. Métodos de análises químicas para avaliação da fertilidade do solo. In: Silva FC. Manual de análises químicas de solos, plantas e fertilizantes. 2. ed rev ampl. Brasília, DF: Embrapa Informação Tecnológica; 2009. p. 107-89.

Wadt PGS, Silva DJ. Normas multivariadas para avaliação do estado nutricional de mangueiras cultivar Tommy Atkins, pelo método da Composição da Diagnose Nutricional. Porto Velho, RO: Embrapa Rondônia; 2020. (Comunicado técnico, 412).

Wadt PGS, Silva LM. Faixa de suficiência e definição da posição da folha na avaliação do estado nutricional de pimenta-longa. Científica. 2016;44:431-8. https://doi.org/10.15361/1984-5529.2016v44n3p431-438

Zone PP, Culman SW, Haden VR, Lindsey LE, Fulford AM, Zhao K. Do soil test levels and fertilization with phosphorus and potassium impact field crop tissue concentrations? Agron J. 2020;112:3024-36. https://doi.org/10.1002/agj2.20243