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Nutrient Diagnosis Norms for Date Palm (*Phoenix dactylifera* L.) in Tunisian Oases

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Abstract: Several studies have pointed out the promising use of nutritional diagnosis methods for the determination of optimum nutrient contents in plant tissues. The present investigation was carried out in different oases in Southern Tunisia to determine reference values for the interpretation of leaf analyses of date palm (*Phoenix dactylifera*) Deglet Nour cultivar with the Critical Value Approach (CVA) and the Compositional Nutrient Diagnosis (CND). A database ($n = 100$) of yield and mineral concentrations taken from date palm leaflets in October, at the maturity stage of dates, was used. The yield cut-off between low-yield and high-yield subpopulations, selected from cumulative variance ratio functions across survey data, was 76 kg palm^{-1} and the global nutrient imbalance index (CNDr^2) was 10.06. Critical CND nutrient indices were found to be symmetrical around zero as follows: (1.59; +1.59) for I_N, (−0.44, +0.44) for I_P, (−0.63, +0.63) for I_K, (−0.94, +0.94) for I_{Ca}, (−1.05, +1.05) for I_{Mg}, (−0.80, +0.80) for I_{Fe}, (−0.74, +0.74) for I_{Cu}, (−0.80, +0.80) for I_B, (−0.93, +0.93) for I_{Zn}, (−1.04, +1.04) for I_{Mn}, and (−1.03, +1.03) for the residual value. Compared to CND, the CVA approach shows weak detection of the nutrients that cause nutritional imbalance. CND indices revealed, except for N, the presence of nutrient imbalances and the necessity to correct the mineral nutrition of date palm in the Kebeli oases.

Keywords: foliar diagnosis; CND: compositional nutrient diagnosis; CVA: critical value approach; selecting high-yield subpopulation; critical nutrient indices

1. Introduction

In Tunisia, date palms (*Phoenix dactylifera*) are an important part of Tunisian agriculture. Tunisia is the world's largest date exporter in value and accounts for 16% of the date world trade value [1]. Despite the importance of date palms, available information about the nutritional requirements of the different cultivars are lacking. Nevertheless, determination of the optimum levels of fertilizers could result in higher yield and better fruit quality that could increase farmers' incomes. [2,3]. To improve fertilization and cultural practices, soil testing is a tool for assessing the amount of plant-available nutrients in the soil. Soil samples should be taken where the plant roots are concentrated and where

the mineral absorption is optimal [4], i.e., between 0.90 and 1.50 m depth and laterally up to the vertical projection of the palm tree canopy. In the case of the Deglet Nour cultivar, lateral roots were found up to 10.5 m from the trunk [5], while penetrating a similar depth. Soil is practically impossible to sample at this deepness. For this reason, the use of leaf nutritional assessments is a promising way to identify the mineral status of date palms. Foliar analysis may identify nutrient disorders in plants, which could not be revealed by visual observations. Observable signs of nutrient imbalance appear when important and irreversible damage has occurred, which results in yield loss or crops growth damage [6]. Moreover, these imbalances could be mistaken as infection diseases, water stress or an excess or deficiency of nutrients [7]. Leaf tissue norms to diagnose nutrient disorder for date palms have not been established yet and the little research completed focuses more on responses to fertilization [2,8–12] or on the dynamics of nutrient concentrations in the organs of date palms [1,13,14]. For these reasons, date palm foliar norms should be investigated for better fertilization practices. Norms developed locally allow for accurate field diagnoses. Many researchers have shown higher precision in diagnosing imbalances when using locally developed norms. Bendaly Labaied et al. [15] found that the norms developed specifically for Tunisian cultivars of mandarins are different from those developed in other countries because of the differences in cultivation practices, cultivar varieties, climate and soil conditions. Establishing foliar analysis norms can be based on a wide variety of interpretation tools such as the Critical Value Approach (CVA), the Diagnosis and Recommendation Integrated System (DRIS) and the Compositional Nutrient Diagnosis (CND) [16]. The CVA method is a conventional univariate method that is widely used and assumes that all nutrients are available and do not constitute limiting factors for the yield. However, the CVA method does not account for interactions between mineral nutrients; interactions that are important for plant nutritional balance, and which are used by DRIS and CND [17]. Some authors have found that there is little differences between DRIS and CND for identifying nutritional deficiencies [15,18–21] but other researchers have found the CND more efficient to determine the nutritional status of crops because its sound mathematical development and firm statistical bases [22–24]. The objectives of this paper are to develop CND and CVA foliar norms for date palms (*Phoenix dactylifera*) of the Deglet Nour cultivar, grown under the specific Tunisian desert conditions and to validate their accuracies in nutrient diagnosing.

2. Materials and Methods

2.1. Study Site

A survey was carried out in the Southern Tunisia during two seasons (2016–2017 and 2017–2018) in one hundred Deglet Nour cultivar date palm orchards located in the continental Saharan oases of Kebeli. These orchards are located in four different pedoclimatic regions: Souk Lahad (33.7785° N, 33.483962° E), Blidet (8.883759° N, 8.854399° E), Nouail (33.578736° N, 33.665074° E) and El Gattaya (8.833898° N, 8.885397° E). These regions represent about 60% of date palms production in Tunisia [25]. The study area has an arid climate with a normal annual precipitation of 80 mm. The normal annual temperature is 20 °C with maximum values of up to 42 °C in summer (August) and minimum values as low as −2 °C in winter (January) [26]. In these regions, date palms grow in traditional and modern oases with Deglet Nour as the main cultivar. Only palm trees with dates were selected and they ranged from 10 to 60 years of age. Yield ranges from 10 to 200 kg palm^{-1} and irrigation is carried out principally by flooding basins. Soils are sandy and alkaline with a pH up to 8. Farmers use mostly manure (20–50 kg per date palm tree every two years) to meet the plant's nutrient requirements and in some cases mineral fertilizers, mainly ammonium nitrate, at the rate of 0.5–0.9 kg per date palm tree. Palms receive all the other required horticultural cares for commercial production, such as pollination, which occurs between March and May, and fruit thinning by reducing the number of fruits per strand in order to enhance fruit quality.

2.2. Leaf Nutrient Concentration Data

To develop diagnostic norms, a dataset of nutrient concentrations and corresponding yield was developed. A sample of 10 healthy date palms in each grower was randomly selected. The sampling was carried out in October, at the maturity stage of dates (Tamer stage) from leaves near the date bunches. The leaflets were taken from the middle portion of the rachis which represented the average concentrations for the various nutrients according to the recommendations of Krueger [1]. A composite sample, containing a minimum of 20 leaflets, was taken from each side (N−S−E−W) of the palm dates. In the laboratory, leaflets were cleaned with distilled water, dried in a forced-air circulation oven at 80 °C until constant weight, and ground to 0.5 mm. The leaf samples were prepared for elemental analyses of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), manganese (Mn) and zinc (Zn) through destruction of organic matter by dry ashing at 500 °C for 4 h. Plant samples were subjected to digestion with a sulfuric acid solution for determination of N content, and nitric digestion for the other nutrients, except boron (B) [27]. After dry digestion, B content was determined by colorimetry using the azomethine-H method [28]. P content was determined using the molibdo-vanadate method (colorimetry) described by Miller [29]. N content was determined by distillation using the Kjeldahl method [30]; nutrients Ca, Mg, Fe, Mn, Cu, and Zn contents were assessed using atomic absorption spectrometry [31] (Thermo Scientific iCE 3500, Thermo Electron Manufacturing Ltd., Cambridge, UK).

2.3. Critical Value Approach

The Critical Value Approach (CVA) was used to determine nutrients' critical ranges for leaves. Envelope curves were plotted that relate nutrient contents to plant yields. The sufficiency interval corresponds to the intersection of the envelope curve with the horizontal line representing 90–95% of the maximum yield of the whole population [32,33].

2.4. Theory of the CND Approach

2.4.1. CND Calculation Procedure and CND Indices

The CND diagnostic approach applied in this study was adopted from that of Khiari, Parent and Tremblay [19], who show that plant-tissue composition can be represented by a d-dimensional nutrient arrangement, i.e., a Simplex (S^d) with $d + 1$ nutrient proportions (d nutrients plus a residual value):

$$S^d = \{(N, P, K, \ldots, R_d), \ N > 0, \ P > 0, \ K > 0, \ldots, R_d > 0, \ N + P + K + \ldots + R_d = 1000\} \quad (1)$$

where $N, P, K \ldots$ = concentration of the nutrients in the dry matter (g kg^{-1}); R_d = residue or concentration of the unmeasurable nutrients in the dry matter (g kg^{-1}); and d = number of nutrients evaluated. As the nutrient proportions become scale invariant after they are divided by the geometric mean G (Equation (2)) of the $d + 1$ components, including R_d [34], the row-centered log-ratio of each sample is calculated (Equation (3)):

$$G = (N \times P \times K \times \ldots \times R_d)^{\frac{1}{d+1}} \quad (2)$$

$$V_N = \ln(\frac{N}{G}), \ V_P = \ln(\frac{P}{G}), \ V_K = \ln(\frac{K}{G}), \ldots, V_{Rd} = \ln(\frac{Rd}{G}) \quad (3)$$

The means (in the high-yielding subpopulation) and standard deviations (in the total population) of row-centered log-ratios of the nutrients concentrations are noted as $V^*_N, V^*_P, V^*_K \ldots V^*_{Rd}$ and SD_N, $SD_P, SD_K \ldots SD_{Rd}$, respectively.

The CND indices, noted $I_N, I_P, I_K \ldots I_{Rd}$, were calculated from the row-centered log-ratios:

$$I_N = \frac{V_N - V^*_N}{SD_N}, I_P = \frac{V_P - V^*_P}{SD_P}, I_K = \frac{V_K - V^*_K}{SD_K}, \ldots, I_{Rd} = \frac{V_{Rd} - V^*_{Rd}}{SD_{Rd}} \quad (4)$$

The CND indices (Equation (4)) are standardized and linearized variables with dimensions of a circle ($d + 1 = 2$), a sphere ($d + 1 = 3$), or a hyper-sphere ($d + 1 > 3$) in a d + 1 dimensional space. The CND nutrient imbalance index $CNDr^2$ of a diagnosed specimen is computed from the CND nutrient indices:

$$CNDr^2 = I_N{}^2 + I_P{}^2 + I_K{}^2 + \ldots + I_{Rd}{}^2 \qquad (5)$$

2.4.2. The Five Steps of CND Norms Development

2.4.2.1. Mathematical Approach for Selecting the High-Yield Subpopulation

The first step consists of determining the cut-off value between low-yield and high-yield subpopulations by relating the cubic cumulative variance ratio functions, $F_i^C(V_X)$ for each nutrient with their corresponding yields Y (Equation (6)) [19]. These relationships result in sigmoidal functions showing a change in concavity at the inflection point corresponding to the cut-off yield. This value of productivity for each nutrient is obtained by solving for the second derivative of the cubic function (Equation (7)).

$$F_i^C(V_X) = aY^3 + bY^2 + cY + d \qquad (6)$$

$$Y = \frac{-b}{3a} \qquad (7)$$

After determining the yield cut-off, nutrient concentrations of the high-yield subpopulation are used to generate the first part of CND norms, which are the means, and standard deviations of row-centered log-ratios from the high-yield subpopulation and the total population, respectively. Detailed development of this approach appears in Khiari, Parent and Tremblay [19].

2.4.2.2. Derive the Theoretical Threshold Global Nutrient Imbalance Index

The second step is the determination of the $CNDr^2$ critical value, which has a chi-square distribution function, since it is the sum of all independent, standardized and squared CND indices (Equation (5)). The $CNDr^2$ threshold is obtained with a chi-square probability function with ($d + 1$) degrees of freedom. For this purpose, we use the ratio of the number of observations of the low yielding subpopulation over the total number of observations, as an exact probability of the cumulative chi-square distribution function.

2.4.2.3. Validate the Threshold Global Nutrient Imbalance Index

The two critical yield (Section 2.4.2.1) and critical chi-squared $CNDr^2$ (Section 2.4.2.2) values determined in the previous steps are validated in this third step. Plotting the $CNDr^2$ on the X-axis and the yields on the Y-axis for the whole population, and applying the Cate–Nelson partitioning procedure, results in a double partition on the X and Y-axis that should validate the critical chi-squared $CNDr^2$ and the yield cut-off [19,35] respectively.

2.4.2.4. Determination of the Threshold for Each Nutrient Indices

As for the $CNDr^2$ (Section 2.4.2.3), this step also involves applying the Cate–Nelson partitioning procedure to all squared nutrient indices ($I_N{}^2$, $I_P{}^2$ … $I_{Rd}{}^2$) related to yield. The threshold for each nutrient index corresponds to the second part of CND norms.

2.4.2.5. Validation of the Threshold Global Nutrient Imbalance Index

The last step consists in a second validation of the theoretical $CNDr^2$ threshold. After determining critical values of the $d + 1$ critical squared indices ($I_X{}^2$) with the Cate–Nelson partitioning procedure, their sum $I_N{}^2 + I_P{}^2 + I_K{}^2 + \ldots + I_{Rd}{}^2$ must be close to the $CNDr^2$ threshold determined in step 2 (Section 2.4.2.2) and validated in step 3 (Section 2.4.2.3). Since these indices are additive when squared, their squared sum must be equal with this critical $CNDr^2$.

2.5. Statistical Analysis

The parameters of the CND Equations (1)–(7) were calculated using Excel® (2010) spreadsheets. A binary classification, which allowed us to separate between the population of stable nutritive composition and that of the unbalanced nutritive composition, was performed based on the Cate–Nelson partition [36]. Optimizing this binary classification was performed with the R software [37].

3. Results and Discussion

3.1. Critical Value Approach (CVA)

Sufficiency intervals obtained with the critical value method are presented in Table 1 for all 10 nutrients (N, P, K, Ca, Mg, Fe, Cu, B, Zn and Mn) and in Figure 1 for N (to illustrate the CVA approach). The lower values of the sufficiency range are the minimal critical points, whereas the higher values are the toxic critical points. These two critical foliar concentration values correspond to 90–95% of the maximum yield [32,33] on the yield envelope curve (Figure 1). As shown in this figure for nitrogen, the two critical values—11.7 g kg^{-1}, above which yield peaks, and 17.0 g kg^{-1}, above which yield falls—form the optimal range. In this envelope curve approach, the critical yield applied is 190 kg palm^{-1}, which is 95% of the maximum yield of 200 kg palm^{-1} recorded in this study area for the cultivar Deglet Nour.

Table 1. Nutrients sufficiency range of the date palm (*Phoenix dactylifera*) nutritional diagnoses obtained with the critical value approach. R^2 is the coefficient of determination between yield and leaf nutrient concentration.

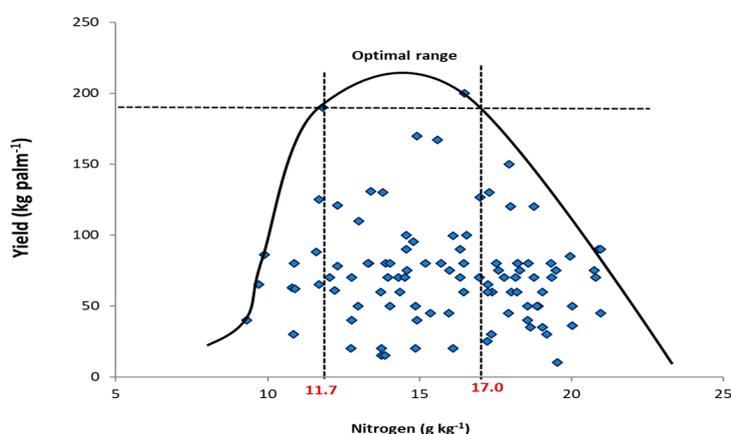| Nutrients	Optimal Ranges	R^2
N (g kg^{-1})	11.7–17.1	0.14
P (g kg^{-1})	0.7–0.8	0.14
K (g kg^{-1})	2.0–2.7	0.02
Ca (g kg^{-1})	7.1–10.8	0.30
Mg (g kg^{-1})	1.4–2.2	0.09
Fe (mg kg^{-1})	160–206	0.06
Cu (mg kg^{-1})	0.84–2.74	0.05
B (mg kg^{-1})	14.74–18.45	0.59
Zn (mg kg^{-1})	6.00–8.00	0.05
Mn (mg kg^{-1})	26–82	0.56

Figure 1. The relation between leaf nitrogen (N) concentration and yield for Tunisian date palm (*Phoenix dactylifera*) orchards (*n* = 100) and the optimal range associated with maximal yield which was calculated based on the envelope-curve technique (Critical value approach).

This CVA approach is especially important in establishing the lower limits of these optimal ranges. All other foliar diagnostic elements were treated in a similar manner to N and their results are summarized in Table 1. Leaf norms of date palms are not yet developed and the few existing studies are limited to the evolution of mineral nutrients during the growth cycle. In our study, leaf mineral contents of the Deglet Nour cultivar are different depending on the southern region of Tunisia from which they come.

Kolsi-Benzina and Zougari [14] measured leaves nutrient contents, which vary between (8–13) g kg^{-1} for N, (0.5–1.0) g kg^{-1} for P, (0.4–8.0) g kg^{-1} for K, (1.8–3.2) g kg^{-1} for Ca, and (9.8–25.7) g kg^{-1} for Mg. The differences between our values and those of Kolsi-Benzina and Zougari [14] are possibly due to the sampling date of fall and the spring (during pollination), respectively. The values of Table 1 are not similar to those from other countries, even though the same sampling and testing protocols were used. For Zaghloul, cultivar date palms grown in Egypt, Marzouk [38] demonstrated that foliar nutrient concentrations varied within the following intervals (units of g kg^{-1}): (21.3–24.4) for N, (2.2–3.4) for P, (16.0–19.8) for K, (1.07–1.44) for Ca, and (2.2–3.4) for Mg, and (units of mg kg^{-1}): (103–134) for Fe, (24–46) for Zn, and (30–50) for Mn. Locally or regionally developed norms produce a higher degree of precision because many factors related with yield or date quality may change: cultivar, rootstock, climate, soil, and crop management [15,16,39]. Although it has been criticized [40,41], the CVA approach remains the most commonly used to diagnose foliar status. Table 1 is useful for advisory services for the quantitative diagnosis of palms. These services prefer to start with this primary interpretation of nutrient deficiency, sufficiency or excess. However, this does not take into account interactions between nutrients and the environment-limiting factors which could have an impact on the plant mineral composition [40,41]. As shown in Table 1, the R^2 values between yield and leaf nutrient concentrations are weak, possibly due to uncontrollable factors such as climate, biotic stress and tree fertility that vary from one year to another and might determine the nutrient responses. Parent et al. [42] showed that multi-nutrient analyses (such as DRIS and CND), taking into account the interaction between different nutrients, is more efficient and correlated with yield more than the single nutrient approach of CVA. In addition to yield, Khiari, Parent and Tremblay [35] found that the CND nitrogen index correlates well with values obtained from a chlorophyll meter. Therefore, the leaf nutrient content is better determined by the Compositional Integrated System (CND) since it is less affected by varying environmental conditions and nutrient interactions in plants [35].

3.2. Compositional Nutrient Diagnosis (CND) Approach

3.2.1. Selecting the High-Yielding Population

All the components of the date palm simplex S^{10}, [N, P, K, Ca, Mg, Fe, Cu, B, Zn, Mn, R$_{10}$] were converted to row-centered log-ratios according to Equation (2), then to cumulative variance ratio functions, $F_i^C(V_X)$, and then related to yield by cubic models according to Equation (6), to finally derive yield cut-off at the inflexion point according Equation (7). The result of these conversions is summarized in Table 2.

The cubic model provided very strong correlations with R^2 between 0.94 and 0.97 (Table 2). With the exception of Mn, yield cut-offs are satisfactory (between 62.48 and 97.88 kg palm^{-1}) according to Tunisian farmers [43], especially for this date palm cultivar. Bouguedoura et al. [44] mentioned that, for a density of 100 palms per hectare, the standard level of the highest yield is 6 Mg ha^{-1} (or 60 kg palm^{-1}) in Tunisia. To select a single yield cut-off, we averaged the 11 critical yield values (Table 2) and obtained a realistic value around 76 kg palm^{-1}. Magallanes-Quintanar et al. [45] used this single average obtained in developing CND norms for Opuntia ficus-indica trees. However, the average date yield in Tunisian oases is about 38 kg palm^{-1} [46]. This widely differs from those of Middle Eastern countries such as Egypt, where they are about 102 kg palm^{-1} [47] or Saudi Arabia, where they are around 60–70 kg palm^{-1} [48]. Considering the 100 palm orchards surveyed in our study, 45 showed a yield higher than the critical value of 76 kg palm^{-1}, the high yielding population

thus becoming 45%. García-Hernández et al. [49] obtained 46.9% using an identical procedure for developing CND norms for Aloe Vera L. in the area of the Baja California Peninsula.

Table 2. Yield of date palms (*Phoenix dactylifera*) at the inflection point ($-b/3a$) of cumulative variance function $F_i^C(V_X)$ for row-centered log ratio in the survey population ($n = 64$).

Nutrient	$F_i^C(V_X)=aY^3+bY^3+cY+d$	R^2	Yield at ($-b/3a$) (kg palm^{-1})
N	$Y = 0.00005x^3 - 0.01169x^2 - 0.22509x + 113.90598$	0.94	75.06
P	$Y = 0.00003x^3 - 0.00695x^2 - 0.33677x + 112.79667$	0.95	75.19
K	$Y = 0.00002x^3 - 0.00519x^2 - 0.40528x + 111.13866$	0.96	74.24
Ca	$Y = 0.00003x^3 - 0.00634x^2 - 0.56267x + 116.52483$	0.95	62.48
Mg	$Y = 0.00003x^3 - 0.00814x^2 - 0.19140x + 110.32916$	0.95	73.84
Fe	$Y = 0.00004x^3 - 0.01102x^2 - 0.15286x + 109.37661$	0.97	77.91
Cu	$Y = 0.00004x^3 - 0.01120x^2 - 0.10562x + 108.39690$	0.97	79.82
B	$Y = -0.000007x^3 + 0.00226x^2 - 0.6316x + 112.6251$	0.97	97.88
Zn	$Y = 0.00005x^3 - 0.01367x^2 - 0.00350x + 108.58952$	0.95	80.10
Mn	$Y = 0.00002x^3 - 0.00434x^2 - 0.85754x + 121.05267$	0.96	48.64
R_{10}	$Y = 0.00003x^3 - 0.00624x^2 - 0.56212x + 111.71052$	0.97	63.27

3.2.2. Theoretical Threshold of Global Nutrient Imbalance Index, CNDr^2

The first CND norms of date palms are presented in Table 3. These norms are the means (of the high-yielding subpopulation ≥ 76 kg palm^{-1}) and standard deviations (of the total population) of the 11 row-centered log-ratios (Equation (3)): V_N^*, V_P^*, V_K^*, V_{Ca}^*, V_{Mg}^*, V_{Fe}^*, V_{Cu}^*, V_B^*, V_{Zn}^*, V_{Mn}^*, and V_{R10}^*. These CND norms were used to calculate the nutrient indices I_N, I_P, I_K, I_{Ca}, I_{Mg}, I_{Fe}, I_{Cu}, I_B, I_{Zn}, I_{Mn} and I_{R10} (Equation (4)) and the CNDr^2 values (Equation (5)).

Table 3. Mean (of the high-yield sub-population ≥ 76 kg palm^{-1}) and standard deviation, SD (of the total population) of foliar concentrations of the 10 nutrients and their row-centered log-ratios transformations (the three columns on the left side are used to determine the first Compositional Nutrient Diagnosis (CND) norms).

Row Centered Log Ratio	Mean	SD	Nutrient Concentration	Mean	SD
V_N^*	3.437	0.200	N (g kg^{-1})	15.8	2.9
V_P^*	0.389	0.206	P (g kg^{-1})	0.8	0.2
V_K^*	1.495	0.395	K (g kg^{-1})	2.4	1.2
V_{Ca}^*	2.737	0.310	Ca (g kg^{-1})	8.0	2.4
V_{Mg}^*	1.329	0.214	Mg (g kg^{-1})	1.9	0.4
V_{Fe}^*	−1.050	0.288	Fe (mg kg^{-1})	180	52
V_{Cu}^*	−5.918	0.634	Cu (mg kg^{-1})	1.6	0.1
V_B^*	−3.236	0.402	B (mg kg^{-1})	21.4	0.8
V_{Zn}^*	−4.346	0.206	Zn (mg kg^{-1})	6.6	0.2
V_{Mn}^*	−2.405	0.533	Mn (mg kg^{-1})	52.0	2.5
V_{R10}^*	7.570	0.096	–	–	–

The CNDr^2 values follow a chi-square distribution ($R^2 > 0.999$, $p < 0.0001$). Because the proportion of the high-yield sub-population is 45%, the proportion with lowest yields (<76 kg palm^{-1}) is 55%. The critical chi-square imbalance index CNDr^2 value corresponding to this proportion is 9.7 for 11 degrees of freedom (Figure 2). This theoretical global nutrient imbalance index corresponds to the maximum value that a date palm can reach while still resulting in a yield ≥76 kg palm^{-1}.

Numerous studies on the development of CND norms confirmed that the larger the size of the simplex, the higher the critical chi-square (χ^2) or critical imbalance index (CNDr^2). In other words, the more nutrients we diagnose in plants, the higher the critical CNDr^2. For sweetcorn and the same database, using two nutrients (N and P with a simplex S^2) led to a critical CNDr^2 of 1.5 [19], whereas

for five nutrients (N, P, K, Ca and Mg with a simplex S^5), this critical value rose to 3.9 [35] and 5.6 [50]. By developing CND norms for greenhouse roses with a simplex S^{11} (size similar to our study), Hermida, Toro, Guzmán and Cabrera [23] found a proportion of 12% of high-yield sub-population and a critical imbalance index ($CNDr^2$) of 7.4, which is lower than our value of 9.7 (Figure 1). Therefore, for the same simplex size, the larger the high-yield sub-population proportion, the higher the theoretical threshold $CNDr^2$. Khiari, Parent and Tremblay [35], and Khiari et al. [51] found that theoretical $CNDr^2$ thresholds are close to the global nutrient imbalance index, $CNDr^2$, calculated in four different situations: two crops (corn, potato) and two simplexes (S^2 and S^5). This step of deducting a theoretical $CNDr^2$ threshold is relevant since it allows for the first global view on the nutrient imbalance when this threshold exceeds the value of 9.7.
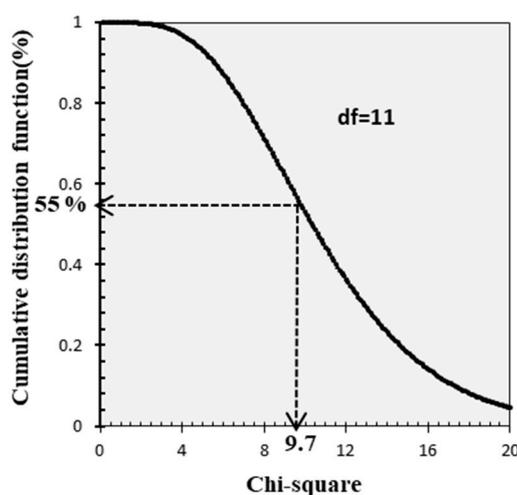

Figure 2. The chi-square distribution function with 11 degrees of freedom used to obtain the theoretical threshold.

3.2.3. Validation of the Nutrient Imbalance Index Threshold ($CNDr^2$)

After calculating the CND indices I_N, I_P, I_K, I_{Ca}, I_{Mg}, I_{Fe}, I_{Cu}, I_B, I_{Zn}, I_{Mn} and I_{R10} (Equation (4)), we found $CNDr^2$ (Equation (5)) and related it to yield according to Figure 3a. Subsequently, we used the Cate–Nelson partitioning procedure and obtained a yield cut-off value of 76.5 kg palm^{-1} and a corresponding $CNDr^2$ value of 10.4. This partitioning procedure resulted in the four quadrants of Figure 3:

- TP true positive (27 points): date palms with high yields are correctly diagnosed with to the global nutrient imbalance index $CNDr^2$;
- TN true negative (38 points): date palms with low yields and correctly diagnosed with $CNDr^2$;
- FP false positive (23 points): date palms with low yields are incorrectly diagnosed with $CNDr^2$;
- FN false negative (12 points): date palms with high yields are incorrectly diagnosed with $CNDr^2$.

The high limit of yield was obtained by minimizing the number of points in the error quadrants (FN and FP) (Figure 3b). The number of points in these error quadrants reached 35 of the 100 from the total population. This minimum corresponds to a yield of 76.5 kg palm^{-1}. Points in the FN quadrant represent high yields but unbalanced nutrition possibly due to excessive fertilization and a negative interaction between nutrients in the simplex S^{10}. In contrast, points in the FP quadrant show a low yield but balanced nutrition, which implies that factors other than nutrition may affect the yield. The Cate–Nelson partition applied to the relationship between $CNDr^2$ and yield allowed us to define a critical $CNDr^2$ threshold of 10.4 (Figure 3c). This threshold corresponds to high points of the curve between the sum of squares and $CNDr^2$ [52]. This critical value allows for the partitioning of the total population into two classes: unbalanced and balanced nutrient status. There is a high

probability that the nutritionally balanced specimens are included in the true positive quadrant (TP) with a $CNDr^2$ of less than 10.4 and yield greater than 76.5 kg $palm^{-1}$. In contrast, there is a high probability that specimens diagnosed with nutritional imbalance will be included in the true negative quadrant (TN) with a $CNDr^2$ greater than 10.4 and yield less than 76.5 kg $palm^{-1}$. The robustness of the Cate–Nelson test is the ratio of the number of points in quadrants TP and TN to the total number of points. In our case, it is 65%, which means that 65% of the total population was correctly diagnosed as nutritionally balanced or imbalanced. The closer the value of R^2 is to 1, the better the robustness [53]. The other calculated performance parameters of this method were specificity (TN/TN + FP), sensitivity (TP/FN + TP), negative predictive value [NPV = (TN/TN + FN)] and, positive predictive value [PPV = (TP/FP + TP)]. These parameters are all positive: 54% for PPV, 76% for NPV, 62% for sensitivity and 69% for specificity when the cut-off yield is 76.5 kg $palm^{-1}$ and the threshold global nutrient imbalance index ($CNDr^2$) is 10.4. The critical $CNDr^2$ value of 10.4 and the yield of 76.5 kg $palm^{-1}$ are close to the cut-off yield determined during the first step (Section 3.2.1, 76 kg $palm^{-1}$) and to the theoretical $CNDr^2$ value determined in the second step (Section 3.2.2, Figure 2: 9.7). The strength of the CND approach, as modified by Khiari, Parent and Tremblay [35] is that it validates the critical global nutrient imbalance index, $CNDr^2$, as described in Sections 3.2.3 and 3.2.5.
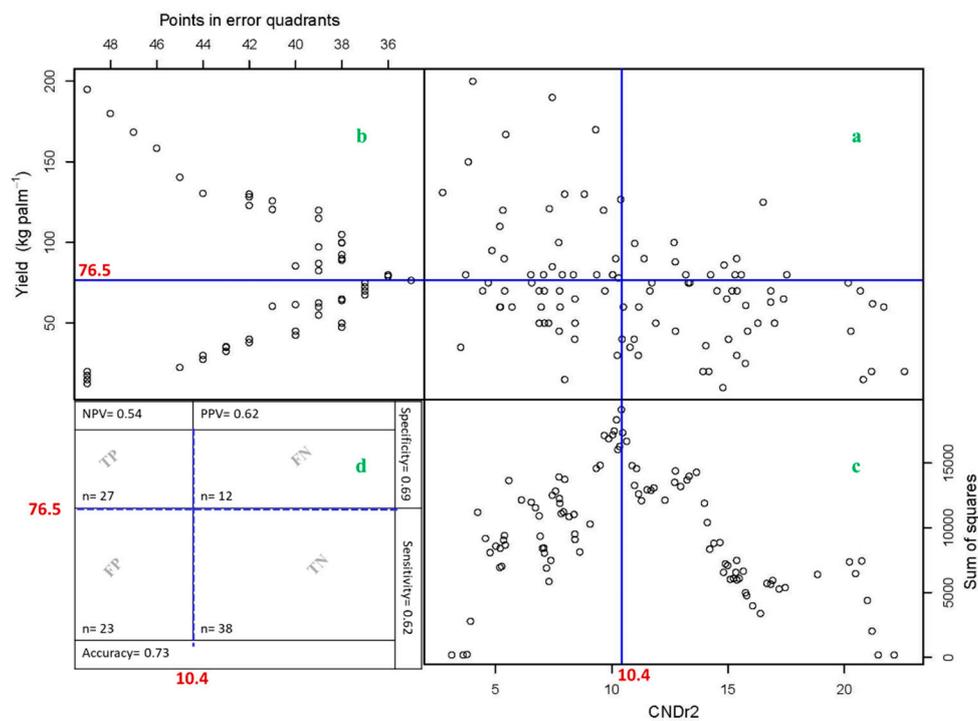

Figure 3. Construction of the diagnostic and statistical model of the Cate–Nelson classification for date palms (*Phoenix dactylifera*) showing: (**a**) Cate–Nelson graph for the $CNDr^2$ with thresholds identified; (**b**) number of points outside the model for determination of the cut-off yield; (**c**) sum of squares for $CNDr^2$ determination; and (**d**) a summary table (lower left); Performance indicators of the partition model are: specificity; sensitivity; accuracy; NPV, negative predictive value; PPV, positive predictive value.

3.2.4. The Sufficiency Range of the Ten CND Nutrient Indices

This step involved applying the Cate–Nelson partition procedure to all squared nutrient indices ($I_X{}^2$) according to yield. The critical squared indices values are the second part of the CND norm. Sufficiency interval indices for each nutrient allow us to establish nutrient standards for the high yielding population (Table 4). In our study, nitrogen represents 24% of the global nutritional imbalance.

Table 4. Threshold CND indices for ten nutrients which are the second part of CND norms using the Cate–Nelson partitioning procedure and the cross validation of threshold nutrient imbalance index $CNDr^2$.

Squared CND Indices for Nutrients	Critical $I_X{}^2$	Critical Range	
		Lower Limit	Upper Limit
$I_N{}^2$	2.53	−1.59	1.59
$I_P{}^2$	0.2	−0.44	0.44
$I_K{}^2$	0.4	−0.63	0.63
$I_{Ca}{}^2$	0.9	−0.94	0.94
$I_{Mg}{}^2$	1.12	−1.05	1.05
$I_{Fe}{}^2$	0.65	−0.80	0.80
$I_{Cu}{}^2$	0.56	−0.74	0.74
$I_B{}^2$	0.65	−0.80	0.80
$I_{Zn}{}^2$	0.88	−0.93	0.93
$I_{Mn}{}^2$	1.09	−1.04	1.04
$I_{R10}{}^2$	1.08	−1.03	1.03
$CNDr^2$ = sum of $I_X{}^2$	10.06	−	

As shown in Table 4, the CND index sufficiency ranges are wider for N ($−1.59 \leq I_N \leq +1.59$), Mg ($−1.05 \leq I_{Mg} \leq +1.05$) and Mn ($−1.04 \leq I_{Mn} \leq +1.04$) than for the seven other nutrients. For example, an I_N value of −1.5 would be sufficient only for N, whereas an I_N value of −1 would be sufficient for N, Mg and Mn but deficient for P, K, Ca, Fe, Cu, B and Zn. Moreover, N, Mg and Mn are the most monitored nutrients and those most frequently tested for the quantitative diagnosis of date palms. The largest sufficiency interval for nitrogen can be explained by the sufficient rates of nitrogen fertilizers provided by growers. Although symmetrical around a mean of zero, the ranges of the CND-I_N intervals would be different from crop to crop. The date palm I_N interval (−1.59; +1.59) is wider than that of potatoes (−0.82; +0.82) and sweetcorn (−0.70; +0.70) Khiari, Parent and Tremblay [35]; therefore, date palms are more tolerant to deficiencies as well as excesses of N.

3.2.5. Cross Validation of the Threshold Global Nutrient Imbalance Index

As the CND is additive for the nutrient indices (I_N, I_P, I_K, I_{Ca}, I_{Mg}, I_{Fe}, I_{Cu}, I_B, I_{Zn}, I_{Mn} and I_{R10}), their sum could be used to validate the critical $CNDr^2$. The sum of the eleven squared individual nutrients indices is 10.1 (Table 4), which is between the critical value $CNDr^2$ of 10.4 obtained at Section 3.2.3 (from a Cate–Nelson partition in Figure 3) and the theoretical value of 9.7 obtained in Section 3.2.2 (derived from the chi-square distribution function in Figure 2). This validation provides coherent results and, therefore, it could be safely stated that the reference population without nutrient imbalance had a yield >76.5 kg palm^{-1} and a threshold $CNDr^2$ = 10.06 (Table 4). These results confirm both the validity of the calculations and the reliability of the CND norms [35].

3.3. Comparison between CVA and CND

Table 5 shows the classification of date palm orchards selected in this study according to established norms. The percentages of three classes, i.e., limited by deficiency (LD), no limited (NL) and limited by excess (LE), are presented for the total population generated and calculated with the two methods CND and CVA. Table 5 shows that values of LD, NL and LE are different for the two methods, especially for N, Ca, B and Zn. This difference might be related to the critical yield considered in defining both norms. The CVA method considers a critical yield of 190 kg palm^{-1} whereas it is 76.5 kg palm^{-1} for the CND method. The value of 190 kg palm^{-1} for the CVA critical yield was determined from the upper envelope of the scatter plot (Figure 1). In the CND method, however, the critical yield was based on a mathematical and statistical optimization (Sections 3.2.1–3.2.5). In addition, the yield cut-off demonstrated that the CND method is more adapted to the Deglet Nour cultivar, farming practices,

climate and soil conditions in Southern Tunisia since it is closer to the highest yield recorded in Tunisian date palms oases [44]. For these reasons, the CND is more reliable and robust than the CVA.

Table 5. Percentages of date palm (*Phoenix dactylifera*) orchards, selected in this study limited by deficiency (LD), not limited (NL) and limited by excess (LE) by nutrients and generated by the Compositional Nutrient Diagnosis (CND) method and the Critical value approach (CVA).

Nutrient	Method	Nutritional Status (%)		
		LD	NL	LE
N	CND	7	91	2
	CVA	8	51	41
P	CND	37	33	30
	CVA	42	24	34
K	CND	16	58	26
	CVA	30	35	35
Ca	CND	25	61	14
	CVA	50	40	10
Mg	CND	8	70	22
	CVA	3	64	33
Fe	CND	23	57	20
	CVA	35	39	26
Cu	CND	17	51	32
	CVA	18	63	19
B	CND	21	61	18
	CVA	25	20	55
Zn	CND	21	64	15
	CVA	43	43	14
Mn	CND	22	63	15
	CVA	24	62	14

According to the CND method, N and P contents are optimal in, respectively, 91 and 33% of the total population. The small proportion of P in optimal content is consistent with the low critical range of I_P. In fact, the critical range of I_P was the lowest (−0.44; +0.44) compared to the other nutrients' critical ranges of N, K, Ca, Mg, Fe, Cu, B, Zn and Mn (Table 4). This weak effect of the P nutrient may be due to a characteristic of the Deglet Nour cultivar, which has a very low P leaf concentration compared to other cultivars. In fact, P leaf contents found in cultivars in Egypt vary from 1.2–7.0 g kg^{-1} [3,54,55], whereas P leaf contents measured in our study were below 1.0 g kg^{-1}, a value close to those found in California for the same Deglet Nour cultivar, Krueger [56]. The high proportion of specimens (91%) in the optimal range of N may be due to farming practices. In most Tunisian date palm oases, the use of manure is, on average, 20 kg palm^{-1}, and mineral fertilizers such as ammonium nitrate, and rarely di-ammonium phosphate, are also provided [57]. N is therefore provided sufficiently. However, this study shows that, aside from N, most date palms suffer from nutritional imbalance. Certainly, N is an essential nutrient for the growth and development of date palms and is often applied alone without being supplemented with other mineral fertilizers [58]. The other nutrients are also important. Many studies focus on the mineral nutrition of date palms in macronutrients and micronutrients and show their importance in improving production in quantity and quality [3,59–64]. In Tunisia, Ben Ammara, Ben Hmida and Ben Mimoun [63] have shown that the yield, date size and leaf nutrient composition significantly increased after potassium fertilization. With foliar zinc, boron and potassium foliar fertilization, Elsabagh [61] obtained a better performance in terms of yield, date quality and control of date palm fruit drop. Other studies have shown the positive impact of more extensive fertilization in terms of N, P, K, S and micronutrients on those performance characteristics for date palms cultivated in very sandy and very nutrient depleted soils [59,64]. The CND method shows that, except for N, most of the diagnosed nutrients can be found outside the none limiting ranges (Table 5).

4. Conclusions

In this study, we developed compositional nutrient diagnosis norms for date palms (*Phoenix dactylifera*), specifically the Deglet Nour cultivar in Kebeli oases in Southern Tunisia. These norms covered ten nutrients (N, P, K, Ca, Mg, Fe, Cu, B, Zn and Mn) taken from leaves near the date bunches in October at the maturity stage of dates (Tamer stage) and were determined using several steps. These steps are presented below with the main results.

- The cumulative variance function allowed us to select a critical yield of 76 kg palm^{-1};
- The χ^2 distribution was used to infer a theoretical critical CNDr^2 of 9.7;
- A Cate–Nelson partition validated the previous two steps by resulting in the same critical yield and critical CNDr^2 of 10.4 close to the theoretical one;
- The same partition was applied to the 10 individual squared nutrient indexes and the following sufficiency ranges were obtained: (−1.59, +1.59) for I_N, (−0.44, +0.44) for I_P, (−0.63, +0.63) for I_K, (−0.94, +0.94) for I_{Ca}, (−1.05, +1.05) for I_{Mg}, (−0.80, +0.80) for I_{Fe}, (−0.74, +0.74) for I_{Cu}, (−0.80, +0.80) for I_B, (−0.93, +0.93) for I_{Zn} and (−1.04, +1.04) for I_{Mn}.
- After cross validation, a validated CNDr^2 was selected (10.06) above which a nutrient imbalance was expected.

Based on the norms established with the two methods, CND and CVA, the diagnosis of nutrients was different. The CND method is more reliable than the CVA since the critical yield considered to generate CND norms is closer to the highest yield recorded in this region of Tunisia. The CND method is also based on a strong mathematical and statistical base.

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