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Research Article

Content and Relationship of Foliar Nutrients in the Presence of the "Duster" Physiopathy in Oil Palm (*Elaeis guineensis* Jacq.)

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The physiopathy of the oil palm (*Elaeis guineensis* Jacq.) called "duster" whose causal agent is unknown is characterized by abnormality in the development of the leaf and longitudinal chlorotic streaking parallel to the midrib. Dissections of plants affected by this disease show no signs at first sight. Therefore, the objective was to explore and evaluate the relationship between some chemical and physical properties of the soils and the content of some elements in the leaves with the presence of physiopathy. Sampling was done of leaflets and the surrounding soil in an oil palm plantation located on the northern coast of Colombia. For the analysis of the data from the foliar analyses, a logistic regression model was used with training and test data. The predictions were contrasted with statistics obtained from the soil data, finding that the affected palms had low S, B and high Fe content in the leaves compared to healthy palms, in addition to obvious differences probably attributable to the K/Mo relationships, Mo/Se, and Z/S. None of these relationships showed a pattern with available soil information.

Keywords: disturbance; nutritional imbalance; physiopathy

1. Introduction

The cultivation of oil palm is the largest in Colombia with almost 600 thousand hectares distributed in four areas of palm, being the agricultural sector that has grown most in the last decade in the country. By 2022, the palm sector had about 7000 producers, with almost 3/4 parts being small producers (less than 20 ha); for this reason, cultivation is associated with progress and the generation of opportunities for the substitution of illicit crops. Its economic importance makes producers concerned about the monitoring of pests and diseases, where the evaluation of the number of bunches, male flowering monitoring and pollinator population, and, without doubt, the appearance of pathologies which could affect the whole plantation are emphasized.

In recent years, the physiopathology of oil palms has been characterized by an abnormality in the development of the leaves: yellowing of young leaves, longitudinal chlorotic streaking parallel to the midrib [1], and the presence of a yellow band (Figure 1). The affected palms show symptoms when they begin production. At present, there is no known causative agent.

In disturbances present in other crops, the nutrient content at the foliar and edaphic levels has been characterized to try to associate them with the presence of the disease. For example, Namsi, Montarone, and Serra [2] reported that date palms (*Phoenix dactylifera*) affected by brittle leaf syndrome have leaflets with lower manganese levels (Mn) compared to the leaflets of healthy palms, even though the soil has adequate Mn levels, so this syndrome

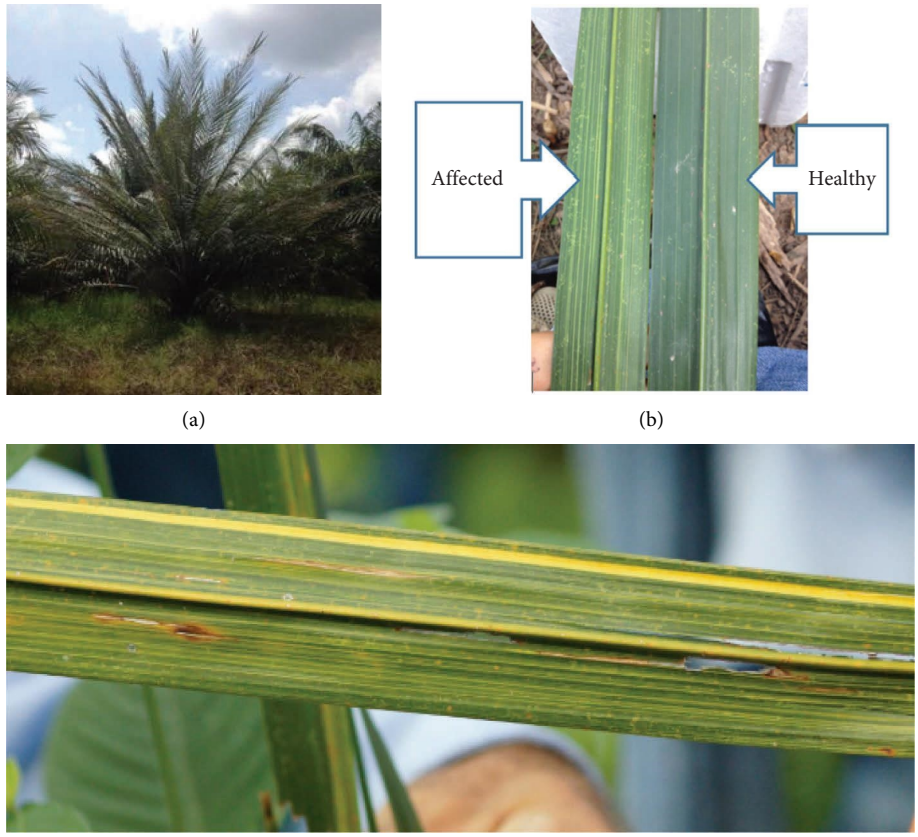


Figure 1: Symptoms of palms affected by "duster" physiopathy: (a) abnormality in the development of the leaf area, (b) longitudinal chlorotic streaking, and (c) yellow band.

cannot be attributed to Mn deficiency [3]. Some authors consider that this disease in date palms is caused by damage to the Mn transporters [4] or possibly because of reduced bioavailability of Mn due to soil pathogens [5].

In oil palm cultivation, several studies suggest that the nutrient content in the soil and in the plant are related to some diseases, for example, in the eastern plains, the soil of the plots with high saturation of Al and low saturation of Mg and K shows a higher incidence of bud rot [6]. The bud rot has been associated with lower levels of S, B, Cu, and Fe, pH, and CEC and higher saturation of Al in soil; meanwhile, lower P, K, and Cu and high Ca and Mg contents have been found in the leaves, as well as higher values in the ratio Ca/B, N/K, Ca/K, and N/P [7].

Several authors have linked the nutritional status of oil palms with pestalotiopsis disease attributable to high concentrations of N and low levels of K in leaf tissue [8]. They even recommend keeping the N/K ratio below 2.3, Ca/K below 0.55, Ca/Mg below 2.3, and (K + Mg)/Ca above 2.3 to reduce the likelihood of this condition. In a plantation in Honduras, the sectors most affected by pestalotiopsis had a low K content and an imbalance of Mg, in addition to very low content of Cu in the foliar tissues. When modeling the disease, they found statistical evidence that P contents and Mg/K, Ca + Mg + K, and Cu/K ratios might be disgusted with the presence of the disease [9].

The objective of this research is to use sampling data to search for patterns related to nutritional content using a logistic regression model with a machine learning approach, where interesting relationships were found between the presence of disturbance and simple leaf contents or in relations of boron, sulfur, iron, potassium, molybdenum, and selenium [10].

2. Materials and Methods

2.1. Location. The plantation of the study is located on the north coast of Colombia; Cesar department (9° 56′ N, 73° 16′ W) Figure 2, at an altitude of 95 m.a.s.l. According to the Köppen-Geiger classification (2018), the plantation is located in the tropical savanna zone at 130 m above sea level, with an annual rainfall of less than 1500 mm and an average temperature of 27°C [11].

Geological formations and surface deposits show different origins, ages, wear dynamics, and deposition in the study area [12]. The most important characteristics of the soils are presented in Table 1.

It is important to note that fertilization and other cultivation activities were carried out according to the schedule established by the plantation, usually guided by the guidelines given in the classic document of Ng et al. and described in Table 2:

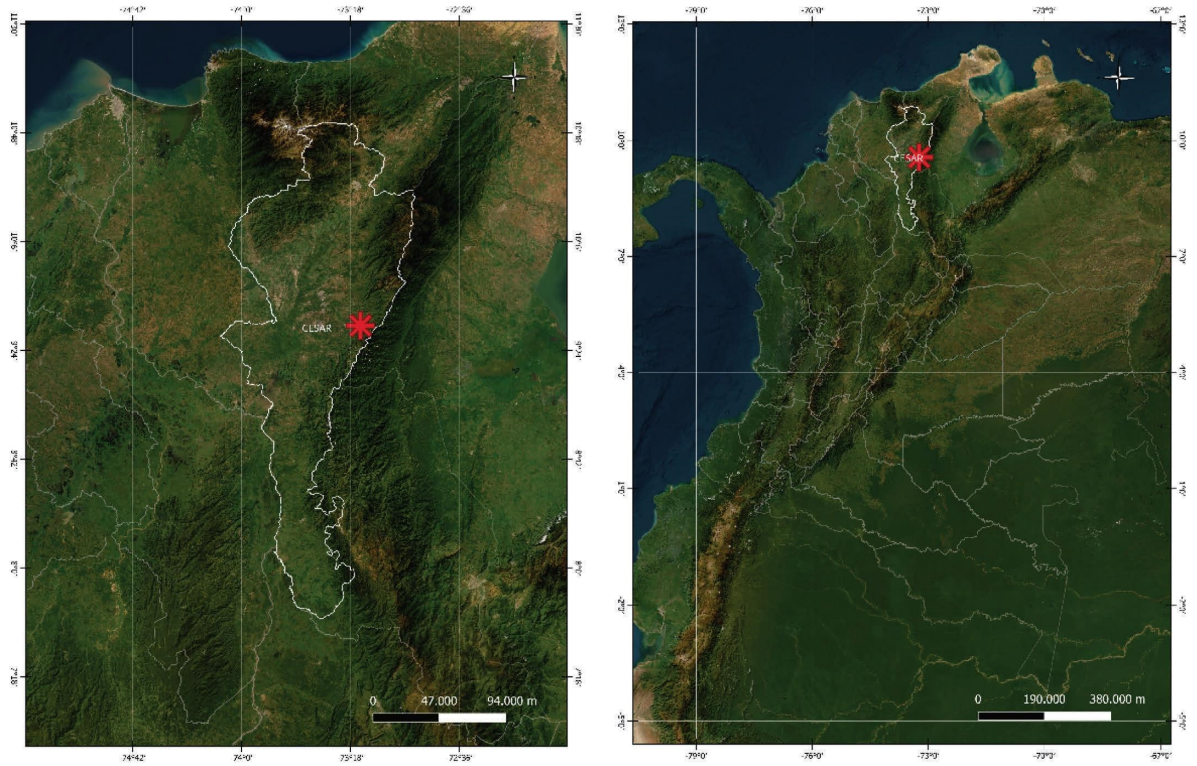


Figure 2: Location of the study department of Cesar, Colombia.

Table 1: Main characteristics of the soils.

Soil classification	Fluventic eutrudepts, typic eutrudepts, typic endoaquerts, and fluventic haplustepts
Erosion and stoniness	Absent
Slope	0%–3%
Fluventic eutrudepts	Very deep with medium internal drainage; slow external drainage; good natural drainage; brown color in the superficial horizons; reddish brown in the deep horizons; loamy-silty clay texture; medium content of organic matter on the surface and very low organic matter in subsequent horizons; high base saturation by Ca, medium for Mg and K and low for Na in the superficial horizon; the last horizon with high contents of P, Fe, Mn, and Cu, medium content of Zn, and low contents of S and B [11]
Typic eutrudepts	Very deep with slow internal and external drainage and good natural drainage; the surface horizon is very dark grayish-brown in color and subsequent horizons are dark brown; loamy texture on the surface and sandy depth and with a subangular blocky structure; low to very low organic matter; slightly acidic pH on the surface, and slightly alkaline in depth with medium cation exchange capacity (CEC) on the surface and low CEC at depth
Typic endoaquert	Very superficially limited by Na by internal drainage as well as externally slow and poor natural drainage; without evidence of flooding or stagnation; presence of expandable clays; low to very low organic content with pH slightly acid on the surface and slightly alkaline at depth; medium CEC on the surface and low in the subsequent horizons; high Ca saturation, medium Mg, K, and Na, with high P contents on the surface and low in depth and in general with low B contents [12]
Fluventic haplustept	Low water storage capacity and low structural stability; loamy to loamy-sandy texture; neutral pH; low organic matter content with a low CEC, high content of Ca, medium Mg and low Na; high content of K in the first 20 cm; low content of S, B, and Zn [9]

Healthy palms and palms affected by PD (Palms of Brabanta origin, Mixed Congo origin and (Ekona × Djongo) × Mongana origin were selected) received the same management within each agronomic management unit. In 2013, complete analyses were made of soil and foliar samples from eight plantation lots, but with different genetic

Table 2: Total soil nutrient content expressed as equivalent nutrient content in direct fertilizers.

Nutrient	Fertilizer (kg/ha)	Fertilizer (kg/palm)
N	456	3.3 (NH_4Cl-25%; annual basis)
P	558	4.0 (jordania-phosphate rock-33% P_2O_5)
K	1212	8.8 (potassium muriate-60% K_2O)
Mg	887	6.4 (kieserite-27% MgO)

origins where cases have been observed. In each batch, five leaf samples were taken per condition to incorporate all the origins and both conditions of the disturbance. Then, soil samples were taken on the plate of healthy and affected palms. To avoid selection biases, hypercube-Latin sampling was used using the location of the palm and row as coordinates and the condition of the palms previously characterized in the lots, as well as the genetic origin, to ensure spatial coverage and genetic representativeness [13]. Using the symptom description in Figure 1, the plantation personnel in charge of identifying the plants affected with the physiopathy were trained to visually qualify the plant as affected or unaffected instead. The samples were analyzed in the nutrient analysis laboratory of Cornell University using the inductively coupled atomic plasma (ICAP) methodology. In the foliar and soil samples, the contents of Al, As, B, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, Sr., Ti, V, and Zn were determined. The matrix of this data is available in the GitHub repository.

2.2. Statistical Analysis. With regard to data analysis, first an exploratory analysis was performed to evaluate the distributional behavior of each variable and for all variables, to detect univariate or multivariate atypical observations (Hotelling diagram T^2), Pearson and Spearman correlation matrices were constructed to note linear or monotonous patterns in the relationships of pairs of variables and to guide both descriptive and inferential analyses to follow, without forgetting that the condition of the palm was available as a classification factor, since the origins were not considered as a factor this time because the cases were selected in a balanced way in each genetic origin. Once the data matrix was refined, two data matrices were organized. These included one for the variables with the results of the foliar analyses and another data matrix with the results of the soil analyzes, together with the presence and absence of the PD for each matrix (data repository). Additionally, new variables were incorporated as a product of the relationships between all the nutrients.

Apart from the descriptive analysis of the set of selected variables, a logistic regression model was used for the inferential component, using the PD presence/absence of data and the foliar physiological variables, modeling the log-odds of occurrence of the event associated with the presence of the disturbance, where p_i represents the probability associated with the ith observation. The model for explanatory variables $(x_{1i}, \ldots, x_{pi})$ writes as:

$$Z_i = \ln\left(\frac{p_i}{(1-p_i)}\right) = \beta o + \beta_1 x_{1i} + \cdots + \beta_p x_{pi}, \quad i = 1, \ldots, n. \tag{1}$$

After adjusting the model and estimating the probabilities of interest, different measures were generated to judge the suitability of the model in the test data, as well as the measures generally used in the epidemiological context, such as sensitivity, specificity, area under the characteristic operating curve, among others, resulting in a very good proportion of correct classifications for the explanatory variables that finally remained in the model.

The logistic regression model was adjusted with a machine learning approach using training data (72%) and test data for the leaf data matrix, no relationship of interest was found for the presence/absence of the disorder in the soil data; therefore, a description of the wide range of soils available was made. For the foliar data, some descriptive measures of each variable were presented based on the results of the adjusted model that included a visual representation of them using boxplot graphs to characterize the distribution of the variable by condition of the palm. The data were analyzed with R studio version 2023.03.0+386 software.

Once the model was adjusted and the cut-off point for the prediction of the disease or its probability was optimized, measures of sensitivity, specificity, percentage of correct classifications, area under the operating characteristic curve (ROC), as well as other measures of fit or suitability of the model involved were noted.

3. Results and Discussion

The logistic regression model for nutrient content in plant tissue that best fitted the data involved the levels of S, B, Fe, and the K/Mo and Mo/Se ratios as possible risk factors (explanatory variables). This was achieved using a variable drop-in algorithm available in R when fitting generalized linear models. They were not always eliminated based on criteria related to the p value, since the issue related to the effect of the third variable (mediation effect or confusion) is well known, meaning that the elimination of certain variables that seemed to match the data does not provide statistical evidence of a null coefficient in the model. The elimination of these apparently not very useful variables from a statistical point of view can significantly destabilize the model (Yu and Li 2022). Therefore, some with p values close to 5% were left in the model, such as the Zn/S ratio (p_value = 0.0553). The final model selected was:

$$E\left(Z_i \middle| x_i\right) = \widehat{\beta}_0 - \widehat{\beta}_1 x_{1i} + \widehat{\beta}_2 x_{2i} + \widehat{\beta}_3 x_{3i} + \widehat{\beta}_4 x_{4i} - \widehat{\beta}_5 x_{5i} + \widehat{\beta}_6 x_{6i}, \tag{2}$$

where E represents the expected value, and the estimated parameters and denotation of the respective explanatory variables are those described in the column labeled variable in Table 3.

Prior to the interpretation of the model, it is important to highlight that the series of measures to evaluate its suitability

Table 3: Estimated parameters of the logistic regression model.

Variable	Estimator	Standard error	Z value	p value
Intercept	$\widehat{\beta}_0 = 26.840$	10.66	2.52	0.0118
x_{1i}: S	$\widehat{\beta}_1 = -0.040$	0.01	−3.50	0.0005
x_{2i}: B	$\widehat{\beta}_2 = 0.088$	0.04	2.13	0.0333
x_{3i}: Fe	$\widehat{\beta}_3 = 0.167$	0.07	2.27	0.0232
x_{4i}: K/Mo	$\widehat{\beta}_4 = 0.001$	0.00	2.66	0.0079
x_{5i}: Mo/Se	$\widehat{\beta}_5 = -118.100$	53.90	−2.19	0.0284
x_{6i}: Zn/S	$\widehat{\beta}_6 = 400.083$	213.10	1.92	0.0553

(Table 4) as well as the confusion matrix of the test data (Table 5) are presented so that the reader can complement their reading and to give the bases for the interpretation of the appropriate model.

All the information in Table 4 are outputs obtained by using Rstudio's glm function to fit the logistic regression model.

The confusion matrix in Table 5 makes it possible to generate the summary of adjustment measures of the selected or trained model. They highlight the predictive capacity of the model of both healthy palms and palms with physiopathy.

It is important to highlight some measures that, rather than characterize the suitability of the model, demonstrate its discriminatory capacity. Starting with the Youden index (Sensibility + Specificity-1), which with a value of 0.727 (relatively high), represented the difference between correct and incorrect positive responses regardless of any specified threshold. In plant epidemiology, the PLR rate provides a measure of how many times more sick plants are likely to test positive than healthy ones (in this case almost 10 times). Similarly, NLR provides a measure of how many times it is more likely that the test (model adjustment) is negative in patients than in healthy ones, so the value close to $0.2 = 1/5$ suggests that it is almost 5 times more likely than the model yields a positive result on diseased plants than on healthy ones. Finally, the odds ratio of presence versus absence of PD yields a value greater than 44, indicating a higher probability of positive occurrence when the disturbance is present.

From a descriptive point of view (Figure 3) and with the results of the model in terms of the variables selected as predictors, we can see how the palms affected by PD have lower leaf S content (Figure 3(a)), B (Figure 3(b)), and the Mo/Se ratio (Figure 3(e)), as well as a higher Fe content (Figure 3(c)) and a higher value of the K/Mo ratio (Figure 3(d)) and Zn/S (Figure 3(f)). The dot in each box represents the arithmetic mean.

Although the structure of the soil data did not allow its modeling together with the foliar analysis variables (because there was only one measurement per plant available), a descriptive analysis was made by palm condition with those variables in which the greatest differentiation was found between healthy and affected (Table 6) as well as a broad description of the type of soils found in the study area. Descriptively we can see that the soil of the palm plates affected by PD had more B and K and a higher K-to-S ratio than healthy palms, and its Fe, S, and Se content was lower.

Table 4: Fit statistics of the logistic regression model.

Extent	Value
Cut point	0.228
Sensibility	0.818
Specificity	0.909
Accuracy	0.864
Area under the ROC curve	0.833
Youden index	0.727
Positive likelihood ratio	8.99
Negative likelihood ratio	0.200
Odds ratio (positive/negative)	44.90
Test data ratio	0.280
AIC of Akaike	54.499

Table 5: Confusion matrix of the binary classification of the adjusted model.

Predicted	Healthy	Affected
Observation		
Healthy	10	1
Affected	2	9

The descriptive intervals were constructed to evaluate the overlap of the measurements in healthy and affected patients; the greater the overlap, the more contrasting the differences. In the case of B, the interval overlapped 54.2%, 80.5% for K, 31.3% for the K/S ratio, and 36.6% for S, so that the most contrasting difference in content was for the K/S ratio followed by S. This shows how the S content in affected palms is lower, and if this value is lower in affected palms, we expected that this yields a higher K/S ratio, as shown in the table, especially when the overlap between healthy and affected for K was higher than 80%, indicating greater similarity between healthy and affected about K, so it can be attributed to an inferior quantity of S in the soil, as happened in the foliar case for this same element.

PD is characterized by abnormality in the development of the leaf area and chlorosis that could be associated with the relationship shown by the model between the S content, since palms affected by PD have lower S content than healthy palms. The low content of S affects the formation of structures, since it is an essential component in the formation of amino acids such as cysteine and methionine, present in all proteins [14]. S is a component of ferredoxin, chlorophyll, enzyme cofactors, sulfolipids, vitamins such as biotin, thiamine, and the formation of peptides such as glutathione and phytochelatins. That is, S is involved in photosynthetic processes, the Krebs cycle, lipid metabolism [15], and mitigation of stress generated by biotic and abiotic agents [16]. Regarding the low level of B, this is usually associated with changes at the anatomical, physiological, and biochemical level, since it has been indicated that it inhibits growth, reduces cell expansion, breaks the tissues due to weakness, and generates abortion of inflorescences and spoilage of fruits. Anatomical symptoms are associated with cell wall abnormalities, and physiological and biochemical changes are secondary effects of cell wall damage [17]. Among the anatomical symptoms is malformation of the leaves [18], a very characteristic symptom of palms affected

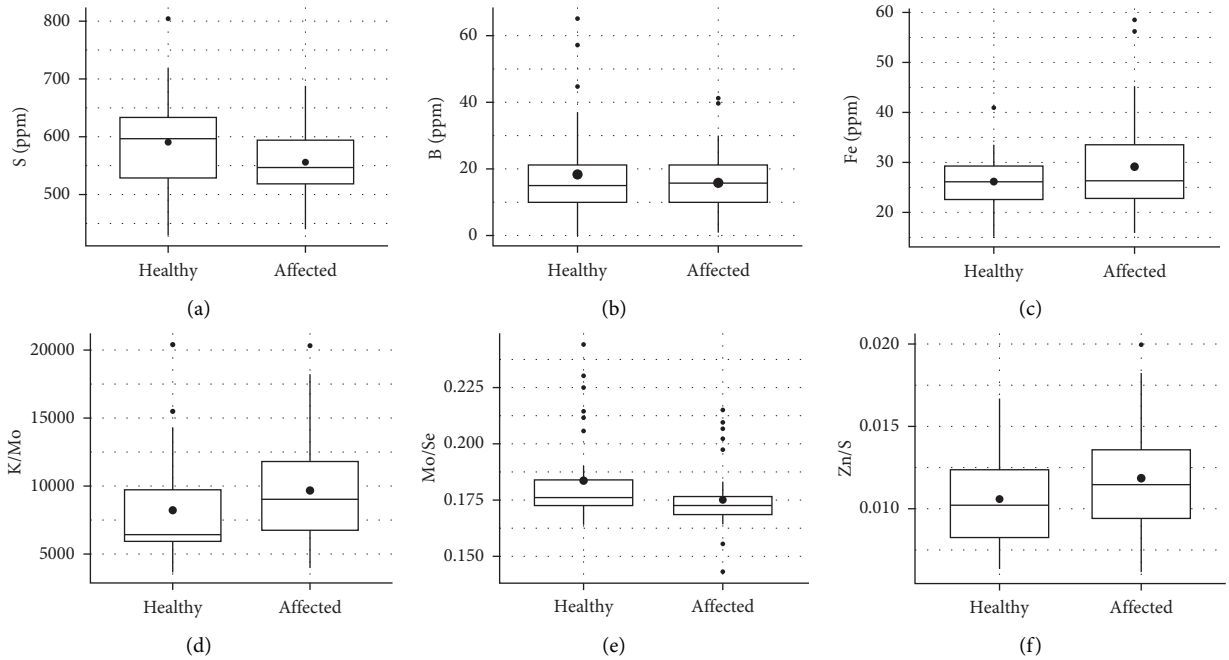


Figure 3: Distribution of the S, B, and Fe contents and the K/Mo, Mo/Se, and Zn/S ratios by palm condition. The data correspond to the complete set (training and test) and the variables are those that showed a non-null effect on the fitted model.

Table 6: Distribution of the content of B, Fe, K, S, and Se in ppm of soil and value of the K/S ratio in soil.

Condition	B (ppm)	K (ppm)	K/S	S (ppm)
Duster	5.59 ± 1.46	2296 ± 819	19.1 ± 6.2	123.9 ± 51.2
Healthy	4.69 ± 1.57	2112 ± 889	12.4 ± 6.6	205 ± 111.8

Note: Each value represents the mean ± the standard deviation.

by PD, and hypertrophy and poor development of vascular bundles [19]. At the physiological level, B deficiency decreases the photosynthetic capacity of the plant and chlorophyll degradation [20] that could also be related to the chlorosis present in the affected palms. Biochemically, there is an increase in the concentration of phenols [21]. In fact, some palms recently affected by PD show purple spots that could be related to the increased concentration of phenols. Some damage caused by B deficiency, such as damage to the structures of the vascular bundles, is hardly reversible, even if the B deficiency was transient [22]. In oil palm, B deficiency generates symptoms such as bifid leaves, hooked leaves, fishbone leaves, leaf blade breakage, and corrugated leaves [23]. Indeed, it is very common to find that palms in initial degrees of duster present some corrugated leaflets, in the shape of a fishbone, even with a break in the leaf blade. B deficiency also generates the chlorotic stripe in seedlings in oil palms [12], a symptom like the yellow band present in all palms affected by DP. In the Mo/Se ratio, the palms affected by PD present a low Mo/Se ratio that may imply a higher Se content or a lower Mo content for fixed levels of the complementary element, and in the current case, the ratio between these two nutrients is due to lower Mo content compared to Se. Low Mo content is associated with whiptail disorder in Brassica crops, while crops such as grapes and beans generate leaf cupping symptoms with and without chlorosis or necrosis. The Mo is related to the metabolism of S, P, and N and is essential in the function of enzymes [24–26], and it is precisely the S element that is proving to be the lowest both in soil and leaf tissue, and for the latter case, it could be due to the effect that Mo itself can exert, since it has been found to be essential in the peroxisomal function of sulfite oxidase that decreases the excess sulfite and aldehyde oxidase, catalyzing the last step of abscisic acid (ABA) biosynthesis. Its deficiency affects the expression of genes involved in ion transport, stress response, and translation signals [27]. Molybdate, the form in which Mo is found in the plant, moves in the plant through its own transporters [4] and through S transporters that are found in membranes, both vesicular and mitochondrial [5, 28]. So, a decrease in sulfate increases Mo accumulation in the leaves [28], and precisely in the palms affected by PD, it occurs under both the S and Mo content. Mo deficiencies in soils generally occur in acid soils rich in Fe and/or Mn oxide [29], and by observation in several areas in the country with acid soils. Cases of palms affected by PD have been identified in soils with a slightly alkaline pH, neutral to slight acid on the surface with high base saturation. The Se increases the antioxidant capacity of the plant, delaying its senescence [30]. The Se is like S in its chemistry and ionic size, so it can replace S in many metabolic processes [31]. The Se shares transporters with the S. In a study where no applications of S were made, an accumulation was observed [23]; however, in the presence of Se, the absorption of S improved [32]. In the palms affected by DP, the S deficiency did not show accumulation of Se and Mo; in fact, a low content of these nutrients was observed. The palms affected by DP had a lower Mo/Se ratio that indicated that they have a higher

content of Se compared to Mo, so the palms affected by PD could be using Se for S in some functions, since it has been pointed out in soybean how selenocysteine and selenomethionine can replace cysteine and methionine [26]. In plants with environmental stress, there is an inverse effect between the content of Se and Fe. Applications of Se decrease the concentration of Fe, because Se helps to restore the structure of chloroplasts [33]. Therefore, when a reduction of Se is observed in the affected plants, it is possible that chloroplast restoration is not being adequately generated in these plants, increasing the Fe levels in the plant [34]. Excess free Fe damages plant cells by enhancing the intracellular production of intermediate reactive oxygen species (ROIs) [34]. Chan, Afton, and Caruso [35] observe in bean plants that Fe overload or oxidative stress increases the production of cytosolic ascorbate peroxidase that is the Fe-containing enzyme that detoxifies ROIs. Fe is indirectly proportional to Mo, since applications of Mo reduce the Fe content [36]. High Fe contents are reported with a low supply of Mo [37]. The Fe content in the leaves also increases when there is loss by root cutting [38]. K functions in plants are linked to processes related to water, cell expansion and turgor-regulated growth, stomatal opening and closing control, long-distance nutrient flow, and nutrient transport across membranes [39]. Palms affected by PD have a low Mo content in relation to the content of K. Grusak, Broadley, and White [40] found that *Brassica napus* plants with Mo deficiency do not generate changes in K uptake, a behavior observed in the oil palms studied. In the same trial, K-deficient plants decrease Mo uptake [40].

4. Conclusions

It was found that the palms affected by PD presented low S, Mo, Se, and B contents at the foliar level, and there was high Fe content compared to healthy palms and no relationship with the nutrient content in the soil for the scenarios studied. When considering the results of the modeling process, one of these is related to the prediction of the condition of the palm. With the observed values of the condition of the plantation and the predicted values of the model, a confusion matrix was constructed, which showed a high percentage of correct classifications (19/22). With these same values, it was possible to obtain the measures of sensitivity, specificity, and Youden's index, remembering that this applies to the test data because in the machine learning approach, a different set was used as training data. This capacity to make correct classifications in spite of being data not used in the construction of the model allows us to speak of the predictive capacity of the model used involving the explanatory variables related to the contents of S, B, and Fe and the K/Mo, Mo/Se, and Zn/S ratios.

Data Availability Statement

The data are available at the GitHub repository address given as follows: https://github.com/darghan/unal/blob/main/cornell_data.xlsx.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Mateo Felipe Fandiño Suarez: graphic development, final document adjustment, bibliography adjustment, and references. Martha Sofia España Guechá and Bernabé Alfonso Rochels Burgos: sample taking and trial monitoring. Ivan Erik Ochoa Cadavid: plantation breeder and person in charge of monitoring the plants within the plantation. Daniel Gerardo Cayón Salinas: specialist in palm cultivation and treatment of crop diseases. Aquiles Darghan Contreras: professor of statistics, processing, and analysis of data.

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