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Impact of Soil Acidity on the Development and Foliar Nutrient Concentration of *Elaeis guineensis* Jacq

Enrique Combatt Caballero[1]*; Luis Alemán Ruiz[1] & Manuel Palencia Luna[2]

[1]*Department of Agricultural Engineering and Rural Development, Universidad de Córdoba, Montería, Colombia*
[2]*Department of Chemistry, Faculty of Natural and Exact Sciences, Universidad del Valle, Cali – Colombia*

**Correspondence: emcombatt@correo.unicordoba.edu.co*

ABSTRACT

In the literature, there is concrete information on the response of oil palm to aluminum saturation; however, it still needs to be discovered how acidity interferes with nutrient absorption in the Elaeis guinennsis Jacq. This investigation aimed to determine the effect of soil acidity on the nutrient concentration and root growth of Elaeis guinennsis Jacq., during the nursery stage. A soil of an acidic nature was subjected to six Al^{3+} treatments (0.0 – 3.5 cmolc kg^{-1}), in which palm seedlings were planted and allowed to grow for seven months. Then, the diameter of the basal bulb and the foliar contents of nitrogen, phosphorus, calcium, magnesium, potassium, iron, and manganese were determined. The results evidenced that an increase in exchangeable acidity reduced root growth and the diameter of the basal bulb. The foliar concentrations of Fe^{3+} and Mn^{2+} were found to be high, and the contents of N and P presented low quantities. Furthermore, the African palm crop resists high Al saturation; however, if it is planted in soils with low nutritional potential of N, P, Ca, Mg, and K and high Al, Fe, and Mn contents in acidic soil, its development will be affected.

Keywords: African oil palm; soil reaction; exchangeable acidity; phytotoxicity & nutritional imbalance

INTRODUCTION

The African oil palm (*Elaeis guineensis* Jacq.) belongs to the monocotyledonous palm family, specifically the *Arecaceae*; this type of palm is a tree that can reach up to 30 meters in height and has a woody stem of approximately 50 cm, on which leaves grow at regular intervals following a double spiral pattern (Meijaard and Sheil, 2013; Woittiez *et al*., 2017). Each of these leaves has a female or male inflorescence, which makes it a monoecious tree, where the harvested cluster can have up to 2000 fruits. From these fruits, oils of great importance in the food (such as cooking oil and margarine), agrochemical (for pesticide production), cosmetic (for skincare and haircare products), and energy (for biofuel production) industries are extracted (Meijaard and Sheil, 2013; Woittiez *et al*., 2017).

The African oil palm's commercial importance is not only due to its diverse industrial applications but also because it is one of the most productive oilseeds (Qaim *et al*., 2020). Thus, its productivity worldwide ranges between 3 to 4 t ha^{-1} of oil per year; however, maximum yields of up to 12 t ha^{-1} per year have been reported (Rival and Levang, 2015). To highlight the comparative advantages of this crop, it is interesting to consider that an average of one hectare of soybean or sunflower generates less than one ton of vegetable oil per year (Qaim *et al*., 2020). On the other hand, African oil palm has wide ecological adaptability in tropical conditions to different taxonomic groups of soils, among which are Entisols, Inceptisols, and highly weathered Oxisols (Meijaard and Sheil, 2013).

The production characteristics of this crop, together with its long functional life (≥ 25 years), and ecological adaptability, have allowed African oil palm to become the primary vegetable oil crop worldwide, with a progressive increase in cultivated area and constituting a source of economic development for tropical regions located in Asia, Africa, and South America (Qaim *et al*., 2020; Woittiez *et al*., 2017). In the case of South America, specifically in Colombia, African palm is one of the perennial crops with the largest planted area, where production is concentrated in four main zones: North, Central, East, and Southwest, comprising 125 municipalities in 25 departments (Fedepalma, 2017). In the northern part of the country, the department of Córdoba stands out; in 2017, it had 4723 hectares planted and is also among the ten departments with the appropriate soil and climatic conditions for planting approximately 3.5 million hectares of African oil palm (CONPES, 2007; Fedepalma, 2017). It is essential to highlight that a proportion of these soils have an acidic tendency, which is not only present in this territory, but it is estimated that 50 % of the soils with agricultural potential worldwide have acidic characteristics (Cui *et al*., 2021).

Thus, soil acidity is one of the limiting edaphic factors for the optimal development and profitability of the crop, since these are exposed to stress factors due to biotic and abiotic problems that affect the biochemical and physiological levels (Bhuyan *et al*., 2019; Cristancho *et al*., 2011; Iqbal, 2012; Meng *et al*., 2019). This is because these soil conditions have been associated with a nutritional imbalance of micro and macronutrients, which generates alterations in the physicochemical and metabolic processes of the palm, resulting in reduced development and an increase in the incidence of diseases (Cristancho *et al*., 2011; Long *et al*., 2017). Previous studies have established that at pH values below 5.5, the toxic forms of aluminum begin to solubilize, generating adverse effects at the root level through a rapid inhibition of root architecture and elongation, resulting in an increased risk of drought (Dorairaj *et al.,* 2020; Siecińska *et al.,* 2019). In addition, these high Al^{3+} concentrations have been related to nutritional imbalances and deficiencies, significantly associated with nutrients such as calcium, potassium, magnesium, and phosphorus (Cui *et al*., 2021). It is essential to highlight that the translocation of high Al^{3+} content affects cell division, integrity, and elongation, the structure and functionality of the plasma membrane, enzymatic activity, and net photosynthetic rate, among others (Cristancho *et al*., 2011; Dey *et al*., 2020).

To understand and mitigate the adverse effects caused by soil acidity on the African oil palm crop, several studies have been carried out on the response of the harvest to these conditions, and management and correction strategies have been proposed, including practices such as liming and the addition of organic matter (Mahmud and Chong, 2022). However, a large proportion of these results are being replicated in different soil and climatic conditions and even with other cultivars, which has generated a broad debate on the tolerance limits of the crop. Thus, in the scientific literature, there are disparate results that establish that the crop can tolerate aluminum saturation of 80 %, 50 %, and even 30 % (Cristancho *et al*., 2011; Munévar, 2001).

In this sense, although data are available on the response of African oil palms to aluminum saturation, there needs to be more information on the response of this genotype to soil acidity and Al^{3+} saturation. Based on this scenario, it is of interest to investigate and analyze the behavior of the African oil palm crop under acid soil conditions derived from aluminum contents. Therefore, this research aimed to determine, during the nursery stage, the effect of soil acidity as a function of adding Al^{3+} on the growth, development, and concentration of nutrients in the leaf tissue of *Elaeis guineensis* Jacq.

MATERIALS AND METHODS

Soil sample collection

To carry out this research, in the first instance, soil samples was collected at a depth of 0 to 20 cm in the municipality of Montelíbano, Córdoba, Colombia, located at coordinates 7° 57' 6.2" N and 75° 27' 40.46" W. The soil sample was then transported to the Soil and Water Laboratory facilities of the Universidad de Córdoba, where one kilogram of soil was used to perform the corresponding characterization and chemical analysis. The remaining sample dried, followed by grinding, and sieving with a pore size of 4 mm.

Physicochemical characterization of the soil sample

The characterization of the exchangeable and available phase of the soil was carried out by determining the following physicochemical parameters: pH by potentiometric method (soil/water, ratio:1/1); exchangeable acidity (Al^{3+} + H^{+}) by titration (KCl 1 M); organic matter content (OM) by Walkley and Black (1934) method; phosphorus content by Bray II method with colorimetric determination (Bray and Kurtz, 1945); sulfur content by extraction with monobasic calcium phosphate and turbidity determination; the range of exchangeable cations (Ca^{2+}, Mg^{2+}, and K^{+}) by extraction with ammonium acetate at pH 7.0 (1 M) and subsequent quantification by atomic absorption spectrometry (Ca^{2+} and Mg^{2+}) and atomic emission (K^{+}) in a Perkin Elmer 3110 instrument; the microelement content (Fe^{3+} and Mn^{2+}) was measured by dilute acid and quantified throughout atomic absorption spectrometry; and the texture was estimated using the Bouyoucos method (IGAC, 2006).

Experimental design

In this research, a complete randomized design with four replicates was used. For this purpose, 16 kg of pretreated soil was deposited in polyester bags, obtaining one experimental unit (EU). Different doses of Al^{3+} were added for each EU, corresponding to 0.0, 0.3, 0.6, 1.1, 1.6, 2.3, and 3.5 cmolc kg^{-1}, using aluminum sulfate salt [$Al_2(SO_4)_3$] as a source of the cation. Distilled water was added to each EU until approximately field humidity was reached, during an incubation period of 15 days. Subsequently, a seedling of *E. guineensis* Djongo: Mongana X Ekona was maintained for 2.5 months in the nursery; after this, one seedling was transplanted in each UE. These UE systems were held in the greenhouse of the Faculty of Agricultural Sciences of the Universidad de Córdoba, located at 15 m.a.s.l. and with the coordinates 8° 48 N and 75° 52' W. A geographical area that is characterized by an average annual rainfall of 1346.1 mm, relative humidity of approximately 84 %, and an average annual temperature of 27.4 °C (Palencia *et al*., 2006). Under these conditions, seedlings were grown for seven months, after which each EU was harvested, and homogeneous samples of 1 kg of soil were collected to determine soil reaction (pH) and exchangeable acidity.

Determination of the dependent variables of the study

After 225 days of applying the Al^{3+} doses, as many roots as possible were extracted from the soil by dry and wet sieving (4 mm). These roots were dried for 72 hours with forced air circulation at 70 °C ± 5 °C in a Binder ED-53 oven. Subsequently, the dry mass of the roots (MSR) and basal bulb diameter (DB, equatorial sine of the bulb) was determined at the height of 1.5 cm from the soil surface, for which a vernier caliper was used.

A systematic approach was followed to determine the concentration of nutrients in the leaf tissue. In the first instance, leaf samples were taken from the third level, these were carefully dried, ground, and sieved in a 0.5 mm mesh. Subsequently, nitrogen was determined by weighing 0.5 grams of leaf tissue from each treatment and using the Kjeldahl method, a widely recognized and reliable method. As for the determination of the other elements, a similar systematic approach was taken. First, 0.3 grams of sieved sample were taken and subjected to digestion with 10 mL of HNO_3; this solution was used to quantify phosphorus by absorption spectrophotometry in a Perkin Elmer Lambda XLS+ equipment; Ca^{2+}, Mg^{2+}, Fe^{3+}, and Mn^{2+} cations by atomic absorption spectrometry, and the K^{+} cation by atomic emission spectrometry in a Perkin Elmer 3110 equipment.

Design and data analysis

The study results were processed with the statistical program R, version 4.0.3 (R Core Team, 2022). For this purpose, a completely randomized design was assumed, where the response variables were studied by analysis of variance ($p < 0.05$) and regression. The coefficient of determination R^2 and the significance of the model's coefficients (β_0 and β_1) were used as adjustment parameters. Finally, Principal Component Analysis (PCA) and Pearson correlation coefficients were performed to study the relationship between the variables.

RESULTS

Physicochemical characteristics of the soil sample

The soil sample presented a clayey texture and a pH of 4.6; this value precisely indicates a strongly acid soil reaction consistent with the high contents of Al^{3+} + H^+ (8.42 cmolc kg^{-1}) encountered. In contrast, the OM (0.17 %), as well as S (10.8 mg kg^{-1}), P (0.4 mg kg^{-1}), Ca^{2+} (1.2 cmolc kg^{-1}), K^+ (0.06 cmolc kg^{-1}), Cu^{2+} (1.2 mg kg^{-1}), Fe^{3+} (16.3 mg kg^{-1}), Zn^{2+} (1.3 mg kg^{-1}), Mn (10.6 mg kg^{-1}), and Na^+ (0.29 cmolc kg^{-1}) contents found are considered lower values. In contrast, the Mg^{2+} contents (1.9 cmolc kg^{-1}) were in the medium range.

Variance analysis

The addition of different concentrations of Al^{3+} to the EUs resulted in significant variations ($p < 0.01$) in edaphic variables such as pH and exchangeable acidity, as well as in the nutritional contents of leaf tissue (N, P, Ca^{2+}, Mg^{2+}, Fe^{3+}, and Mn^{2+}), except for K^+ (**Table 1**). On the other hand, the lowest coefficients of variation (CV) were found in the exchangeable acidity parameters, foliar N and K^+ contents, and in the morphometric variables DB and MSR. As for moderate CV variations, the values found for the atomic species Al^{3+}, Ca^{2+}, Mg^{2+}, P, and Mn^{2+} were between 11.37 % - 18.32 %. Finally, high variations were found for pH (21.16 %) and Fe^{3+} (47.05 %).

Table 1. Results of the analysis of variance of edaphic, morphometric, and nutritional parameters

Variable	CV (%)	CMT	CME	*p* value	Assessment (*p*)
MSR	8.61	59.4522504	10.2474083	0.00108317	<0.01
DB	5.51	34.382303	3.36874315	2.5198×10^{-5}	<0.01
pH	21.16	4.07128095	0.22291071	2.4275×10^{-7}	<0.01
Al^{3+} + H^+	9.98	2.97944048	0.20638095	1.7169×10^{-6}	<0.01
Al^{3+}	11.37	0.59646429	0.05304286	1.2207×10^{-5}	<0.01
N	2.64	0.02693075	0.00445238	0.00084494	<0.01
P	13.80	0.00306662	0.00040555	0.00020587	<0.01
Ca^{2+}	11.98	0.00946979	0.00182295	0.002043	<0.01
Mg^{2+}	13.75	0.01757276	0.0035194	0.0025427	<0.01
K^+	3.00	0.00527337	0.01400367	0.88564594	>0.01
Fe^{3+}	47.04	592728.794	44662.0768	3.372×10^{-6}	<0.01
Mn^{2+}	18.32	102262.499	8848.68398	9.9112×10^{-6}	<0.01

Note:CME: error mean squares; CMT: mean squares of the treatments.

Changes in pH and exchangeable acidity of the soil

The application of aluminum doses in the soil led to a significant decrease in pH, following a decreasing linear trend, as indicated by the mathematical model $y = 5.2941 - 0.6606^{**}x$ (** indicate the significance of the coefficients with probability at 1 %), an equation that explained 70 % of the response between the variables (**Figure 1a**). Thus, for one cmolc kg^{-1} of Al^{3+}, there was a decrease of 0.6606 pH units, and for the dose of 3.5 cmolc kg^{-1}, a pH of 2.98 was obtained, equivalent to a reduction of 43.6 %. Conversely, aluminum contents and exchangeable acidity showed a positive linear trend.

In the case of Al^{3+} determined in the soil samples, the coefficient of determination represents 63 % of the linear correlation between the variables, with a mathematical model of y = 2.7652 + 0.282**x (**Figure 1b**). This model reveals that the dose of 1 cmolc kg^{-1} of Al^{3+} increased by 0.283 cmolc kg^{-1} of Al^{3+} in the soil sample, and the amount of 3.5 cmolc kg^{-1} caused an increase of 0.987 cmolc kg^{-1} of Al^{3+} (35.69 % higher than the control). As for the exchangeable acidity, the data were adjusted with the mathematical model y = 7.0863 + 0.6823**x, presenting a linear correlation of 78 % in the variables, such that by applying one cmolc kg^{-1} of Al^{3+}, the exchangeable acidity in the soil increased by 0.6823 cmolc kg^{-1} (**Figure 1c**). These significant results suggest that the exchangeable acidity (0.6823 cmolc kg^{-1}) is the result of 0.283 cmolc kg^{-1} of Al^{3+} and 0.3993 cmolc kg^{-1} in relation to the content of hydrogen, iron, and manganese cations.

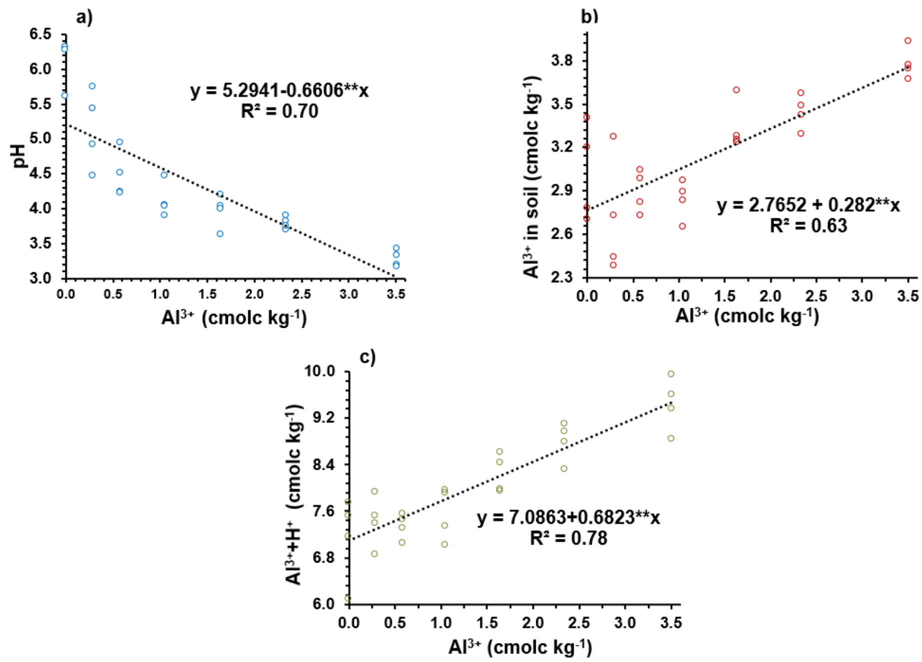

Figure 1. Effect of the application of different doses of aluminum a) on the soil pH, b) the concentration of Al^{3+}, c) and Al^{3+} + H^{+}, in acid soil planted with oil palm seedlings (*Elaeis guineensis* Jacq. var. Djongo: Mongana X Ekona).

Dry mass and leaf area

The application of Al^{3+} doses significantly impacted the dry leaf biomass (DLB), showing a negative linear decreasing trend, according to the model y = 52.894 - 3.8598*x (**Figure 2a**). With this mathematical model, it was found that, for each additional unit of aluminum to the soil, the leaf biomass decreased on average by 3.8598 g. Therefore, the DLB production was reduced by 25.54 % concerning the biomass of the control (52.894 g). Similarly, the leaf area (LA), this, in turn, presented a decreasing negative linear trend, described by the mathematical model y = 9419.5 - 885.33*x, with a concordance of 75 % of the linear trend based on the R^2 value (**Figure 2b**). This is a decrease in the basal diameter of 885.3 g generated for each cmolc kg^{-1} of Al^{3+} added to the soil. It was highlighted that the dose of 3.5 cmolc kg^{-1} of Al^{3+} caused a reduction of 3098.6 g, equivalent to a decrease of 32.89 % regarding the control.

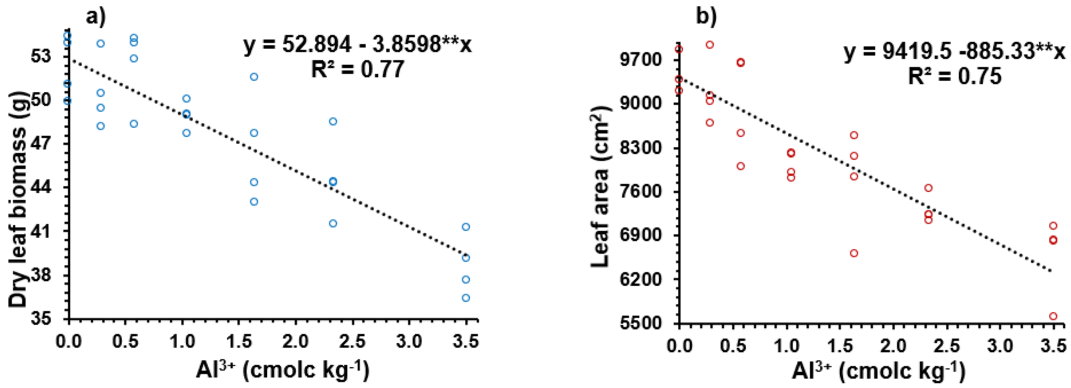

Figure 2. Effect of aluminum on a) root biomass and b) leaf area in oil palm seedlings (*Elaeis guineensis* Jacq. var. Djongo: Mongana X Ekona) planted in acid soil.

Changes in the content of foliar nutrients

Foliar content of nitrogen and phosphorus

Leaf N content showed a negative linear decreasing trend as a function of Al^{3+} addition. This trend agrees with the mathematical model y = 2.9666 - 0.0631**x, which explains the 58 % correlation between the variables (**Figure 3a**). Through this equation, it was determined that, for each additional unit of aluminum in the soil, N decreased by 0.0631 %, highlighting that for the dose of 3.5 cmolc kg^{-1}, the N content was 2.74 %, a value lower than those proposed by Fairhurst and Härdter (2003), who indicated a critical value for N lower than 3 %. Likewise, P contents in leaves decreased linearly with the increase of Al^{3+}, a trend that was adjusted to the model y = 0.2121 - 0.0196**x (**Figure 3b**). Thus, a reduction in leaf P content of 32.34 % was established at the maximum aluminum dose (3.5 cmolc kg^{-1}). The average leaf P contents found were lower than those proposed by Fairhurst and Härdter (2003), who indicated that the critical value of P is lower than 0.25 %.

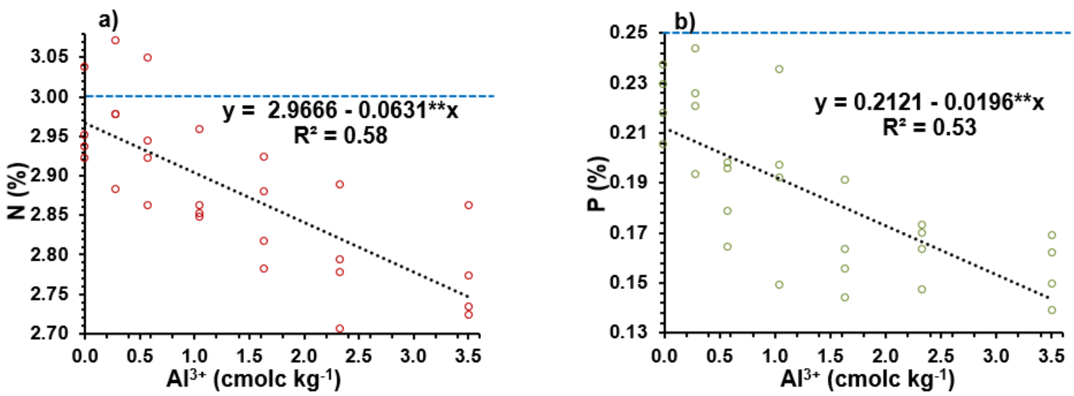

Figure 3. Effect of aluminum on leaf concentration of nitrogen a) and phosphorus b) in oil palm (*Elaeis guineensis* Jacq. var. Djongo: Mongana X Ekona) seedlings planted in acid soil. The blue line corresponds to the percentage limit proposed by Fairhurst and Härdter (2003).

Foliar content of calcium, magnesium, and potassium

The leaf contents of Ca^{2+}, Mg^{2+}, and K^{+} showed a linear decreasing trend with increasing doses of Al^{3+}. Specifically, the leaf calcium content was modeled with the expression y = 0.4308 - 0.0355**x, representing 60 % of the linear relationship between the variables (**Figure 4a**);

thus, an increase of 3.5 cmolc kg^{-1} of Al^{3+} represented a decrease of 28.84 % of Ca^{2+} in the leaf tissue. Concerning the accumulation of magnesium in the leaf tissue, this was modeled by the trend y = 0.5117 - 0.0485**x, which contains a 62 % relationship between the variables (**Figure 4b**), where the accumulation of Mg^{2+} presented a reduction equivalent to 33.17 % with the dose of 3.5 cmolc kg^{-1} of Al^{3+}. On the other hand, in the case of potassium, the decreasing trend followed the mathematical model y = 1.1925 - 0.0552**x, with a reduction of 16.2 % at the maximum dose of Al^{3+} (**Figure 4c**). The foliar contents of Ca^{2+}, Mg^{2+}, and K^{+} found were lower than those proposed by Fairhurst and Härdter (2003), who established that the critical values of these cations are lower than 1.0, 0.7, and 1.6 %, respectively.

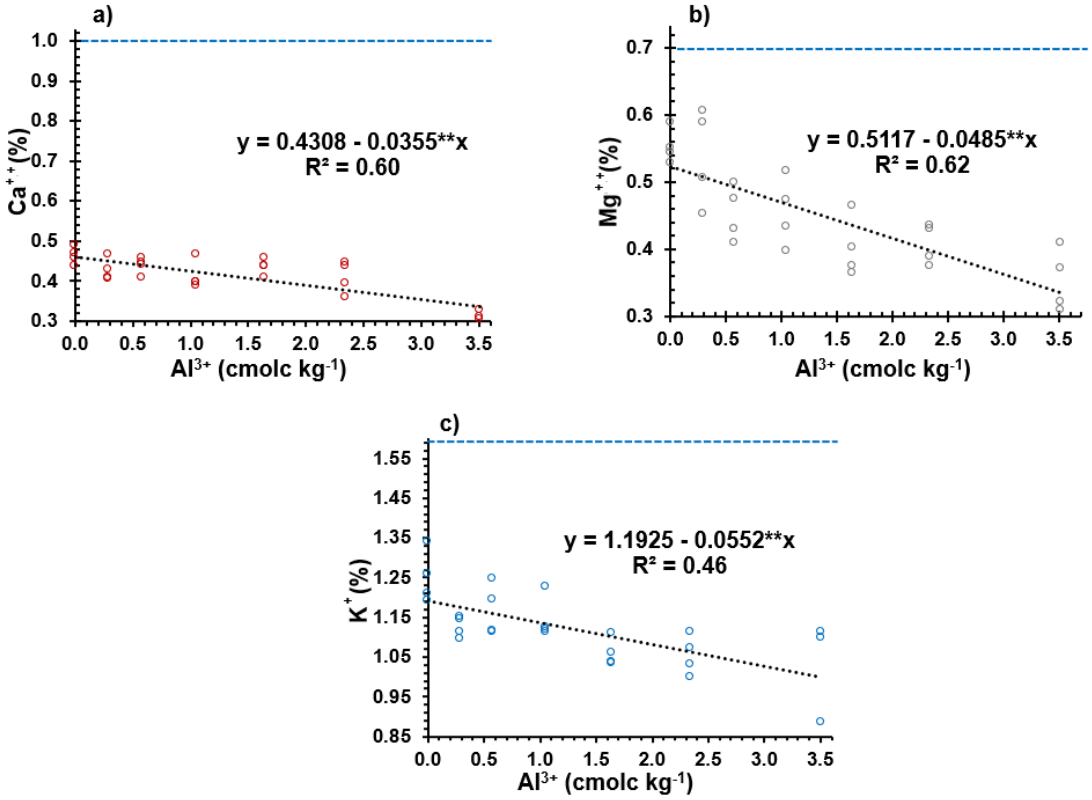

Figure 4. Effect of aluminum on the foliar concentration of a) Ca^{2+}, b) Mg^{2+}, c) and K^{+} in oil palm seedlings (*Elaeis guineensis* Jacq. var. Djongo: Mongana X Ekona) planted in acid soil. The blue line corresponds to the percentage limit proposed by Fairhurst and Härdter (2003).

Foliar micronutrient contents

Foliar Fe^{3+} contents showed a positive response with increasing exchangeable acidity of the soil, according to the mathematical model y = 426.5 - 242.23**x, with an adjustment of 78 % (**Figure 5a**). In this sense, the dose of 3.5 cmolc kg^{-1} of Al^{3+} increased iron accumulation in leaf tissue, equivalent to 190.5 %. On the other hand, the foliar Mn^{2+} contents also presented a positive response associated with the increase in Al^{3+} content, which was modeled by the expression y = 689.04 - 119.18**x, which exhibited a linear adjustment of 61 % between the variables **(Figure 5b**). Thus, the dose of 3.5 cmolc kg^{-1} of Al^{3+} led to an accumulation of Mn in leaf tissue of 60.5 %. The foliar iron and manganese contents determined in this study were higher than those established by Munévar (2001), with maximum values of 80 and 160 mg kg^{-1}, respectively.

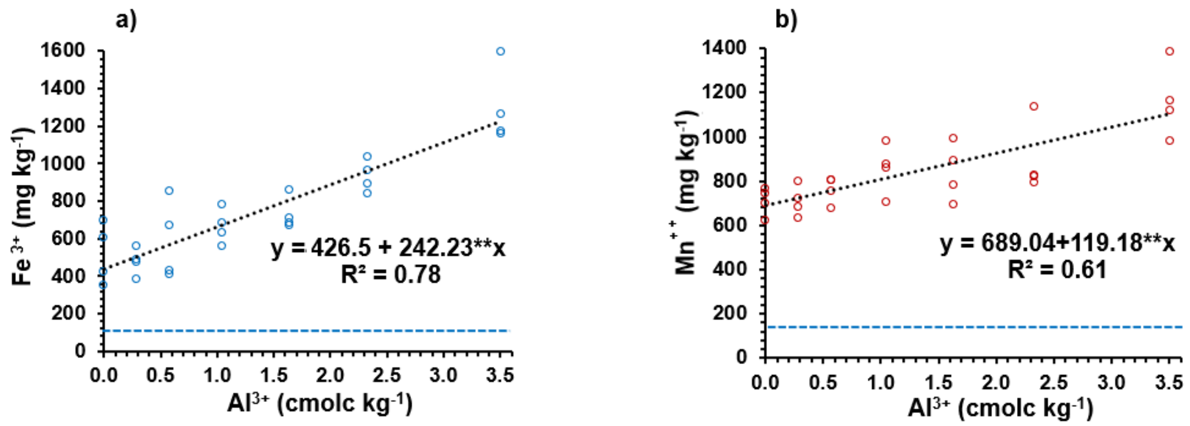

Figure 5. Effect of aluminum on the foliar concentration of Fe^{3+} a) and Mn^{2+} b) in oil palm seedlings

Multivariate analysis between soil acidity and palm foliar and nutritional characteristics

Principal Component Analysis (PCA) was employed to study the effect of Al^{3+} application on soil acidity, nutrient uptake, dry leaf biomass, and leaf area. The PCA results showed that the parameters studied could explain approximately 93.4 % of the variance. The first component evidence that the parameters that presented a more significant contribution to the variance (87.4 %), with a positive correlation between the increase in Al^{3+} concentration, were exchangeable acidity, Al^{3+}, Fe^{3+}, and Mn^{2+} content; and a negative correlation with DLB, LA, pH, Ca^{2+}, and Mg^{2+} (**Figure 6a**). The second component (6.0 %) correlated positively with pH, P, Mg^{2+}, and K^{+}, and negatively with Ca^{2+} content and DLB (**Figure 6a**). Regarding the Pearson correlations between the evaluated parameters, it was determined that there was a negative correlation between the increase in acidity with pH (r = - 0.83, $p \leq 0.05$), DLB (r = - 0.98, $p \leq 0.05$), leaf area (r = - 0.94, $p \leq 0.05$), Ca^{2+} (r = - 0.84, $p \leq 0.05$), Mg^{2+} (r = - 0.87, $p \leq 0.05$), N (r = - 0.94, $p \leq 0.05$), P (r = - 0.85, $p \leq 0.05$) and, K^{+} (r = - 0.88, $p \leq 0.05$) (**Figure 6b**). Likewise, it was found that the increase in exchangeable acidity presented a positive correlation with the content of Al^{3+} (r = 0.93, $p \leq 0.05$), Fe^{3+} (r = 0.96, $p \leq 0.05$), and Mn^{2+} (r = 0.91, $p \leq 0.05$) (**Figure 6b**).

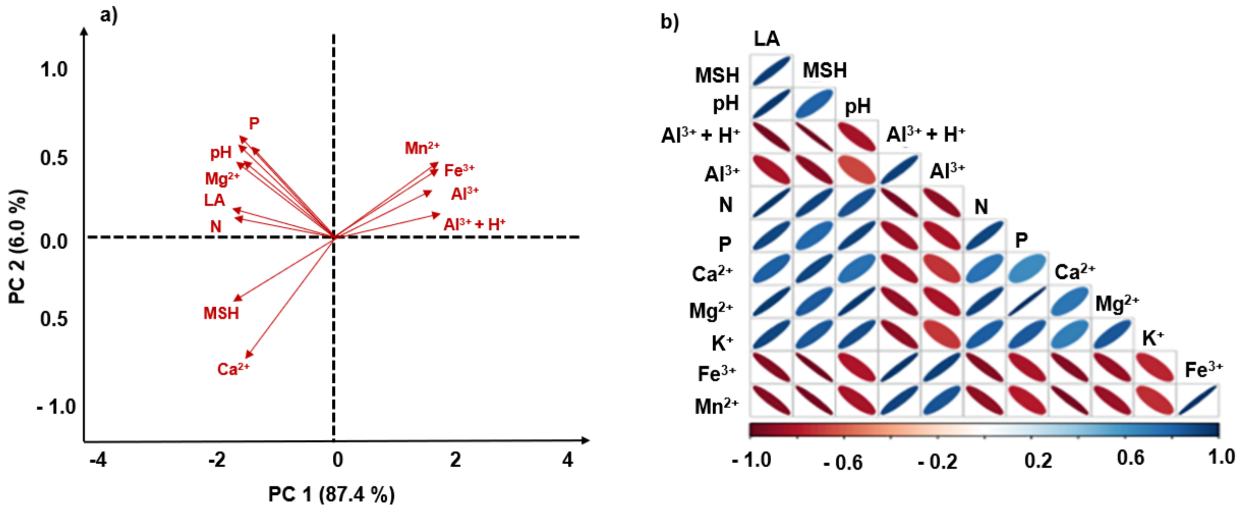

Figure 6. a) PCA and b) correlation of the variables evaluated in the soil and the African palm tissue **4.**

DISCUSSION

Physicochemical characteristics of the soil sample

The physicochemical characteristics of the soil sample from Montelíbano, Córdoba, are in accordance with the representative conditions of acid soils in Colombia, particularly those located in hilly landscapes, subjected to intensive agricultural activity, and presenting prolonged rainfall events during the year (> 2000 mm) (Zhang *et al.*, 2019). Under these soil characteristics, soil acidity and rainfall conditions promote the leaching of a wide variety of essential plant elements, which, through various geochemical and biological reactions, increase the concentration of some elements beyond the crop's tolerance limit (Fageria and Nascente, 2014). In this sense, the nutritional contents found in the studied soil are considered below the normal range for the optimal development of the African palm crop, while the pH value (4.6), mainly associated with the content of hydrogen and aluminum cations, is at the acceptable limit (Zarif *et al*., 2020).

Variance analysis

The analysis of variance of the responses of the edaphic and morphometric variables as a function of adding Al^{3+} confirms that at least one of the doses generated a differential effect; such effects presented inverse or directly proportional tendencies with the aluminum concentration. In general, the results obtained are in agreement with previous research, where artificial or natural acidification of the soil generated a delay in the development and yield of the crop and a decrease in the absorption and concentration of nutrients (Bojórquez-Quintal *et al*., 2017; Pereira, 2018). These appreciations on the differential effects of aluminum on the evaluated variables are described in detail below.

Changes in soil reaction and exchangeable acidity

The results show an inversely proportional response of soil pH as a function of Al^{3+} dosage (**Figure 1a**). This behavior can be explained because, in the soil solution, the presence of Al^{3+} cations allow the hydrolysis of water molecules with the consequent production of hydronium ions, which, in turn, favors the solubility of aluminum compounds, simultaneously increasing the H^+ and Al^{3+} content (Bojórquez-Quintal *et al*., 2017; Yang *et al*., 2015; Zhao and Shen, 2018).

In that sense, the trends found for Al^{3+} contents and exchangeable soil acidity (**Figure 1b and 1c**) are the result of this additive effect because, as previously mentioned, hydrolysis favors the solubilization of non-exchangeable forms of aluminum, among which hydroxides ($Al(OH)^{2+}$, $Al(OH)_2^+$, $Al(OH)_3$, and $Al(OH)^{4-}$), sulfates ($AlSO_4^+$) and organic and inorganic complexes predominate (Bojórquez-Quintal *et al*., 2017; Nogueirol *et al*., 2015). On the other hand, it is relevant to highlight that, in degraded and highly weathered soils, this hydrolysis reaction commonly occurs, and even ion exchange processes (which can increase bioavailable aluminum contents), favored by anthropic activities and high precipitation (Fageria and Nascente, 2014).

Biomass and leaf area of African palm seedlings

The results showed that the biomass and leaf area presented a trend inversely proportional to the Al^{3+} dose (**Figures 2a** and **2b**); results in agreement with the research carried out by Chaffai *et al*. (2005). These physiological manifestations are directly associated with the adverse effects of the Al^{3+} cation on the root system (Cristancho *et al*., 2011). In this sense, the high concentrations of available Al^{3+} in the growth medium allow considerable bioaccumulation of this in the roots, which favors the adherence of anionic functional groups, such as sulfates and carboxylates, to the plasma membrane and cell wall of this system (Shetty *et al*., 2021). This process affects the root's structural properties, leading to a decrease in its permeability in constituted tissues, while in meristematic tissues, there is a decrease in proliferation, viability, and cellular content (Utami *et al*., 2019).

The net effects of these biochemical processes generate an inhibition of root elongation and a deficient functionality, thus affecting water and element uptake, leading to a nutritional imbalance (Sade *et al*., 2016; Souza *et al*., 2105). For example, this condition can be analyzed through the Ca^{2+}/Al^{3+}, Mg^{2+}/ Al^{3+}, and K^{+}/Al^{3+} cation ratios, where the assimilation of alkaline cations decreases at high aluminum contents (Shetty *et al*., 2021). In turn, these nutritional imbalances increase the concentration and accumulation of free radicals in the tissues, generating oxidative stress and affecting the integrity of the cell membrane through lipid peroxidation processes (Shetty *et al*., 2021). In summary, the totality of the biochemical processes occurring in the root, together with the adverse effect on plant functionality and development, translate morphologically into a decrease in biomass gain in the leaf tissue of the palm.

Foliar nitrogen and phosphorus contents in African palm

Figure 3a demonstrates that the N concentration in leaf tissue decreases with increasing Al^{3+} content in the soil sample. This is a result of the nutritional imbalance generated by aluminum ions in the seedlings, derived from the functional and morphological affectation of the root system, which decreases the contact area with the rhizosphere and, therefore, the uptake of nutrients such as N (Zarif *et al*., 2020). This decrease in nitrogen content in the plant generates adverse effects because nitrogen is a fundamental element in essential structures such as chlorophyll, amino acids, genetic material (DNA and RNA), and energy-carrying molecules (ATP and ADP) (Boussadia *et al*., 2010). Therefore, the reduction in N concentration leads to a decrease in the photosynthetic rate and a more significant accumulation of total sugars in the leaf tissue, affecting plant growth and development, which is reflected in a reduction of the production of vegetative biomass (Sami *et al*., 2016).

It is crucial to mention that, despite the decrease in foliar N content, the concentrations are within the minimum requirement ranges for the crop, a statement based on the results published by Rankine and Fairhurst (1999) and Munévar (2001), who established these limits between 2.3 % and 2.9 %, respectively. However, when comparing the research results with those published by Fairhurst and Härdter (2003), the concentrations found are lower than the critical level of 3.0 %. In this sense, it is possible to affirm that the African palm crop shows a slight tolerance to high amounts of Al^{3+} in soils with low nitrogen content and low nutritional potential, i.e., soils considered infertile (Zhang *et al*., 2014).

On the other hand, the behavior of leaf phosphorus content showed a trend analogous to nitrogen concentration (**Figure 3b**), i.e., inversely proportional to the Al^{3+} dose. Specifically, P contents in leaf tissue were found to be within the acceptable nutritional range for *E. guineensis* (0.15 - 0.22 %), according to the research of Ng *et al*. (1999) (0.15 %) and Munévar (2001) (0.18 %). In contrast, the results of Fairhurst and Härdter (2003) indicate that this concentration is lower than the critical level of P, which the author established as 0.25 %.

It should be noted that the trend observed in **Figure 3b** is directly related to the decrease in phosphorus bioavailability in acid soils due to the production of insoluble compounds of the iron and aluminum phosphate type (Johan *et al*., 2021). In addition, the absorption of bioavailable phosphorus is diminished by the effects on root development derived from the exchangeable acidity of the soil, which, together with the reduced mobility of phosphorus in acid soils, results in a low content of this nutrient in the plant tissue (Hanafi *et al*., 2020). This deficiency has essential impacts on the optimal biological functioning of the plant since phosphorus is an element of great importance in processes such as flowering, protein synthesis, meristematic tissue development, energy transfer, photosynthesis, cellular respiration, stomatal conductance, N absorption, and intracellular carbon dioxide concentration (Marschner, 2012; Veronica *et al*., 2017).

Alkaline cation content in African palm leaves

The increase in Al^{3+} content in the soil reduced the absorption and accumulation of Ca^{2+}, Mg^{2+}, and K^{+} cations, finding foliar contents for Ca^{2+} of 0.43 - 0.30 %, Mg^{2+} of 0.51 - 0.34 %, and K^{+}

of 1.19 - 0.99 %. These calcium and potassium contents are lower than the reference levels published by Fairhurst and Härdter (2003), Munévar (2001), and Ng *et al*. (1999), which are in a range between 0.65 - 1.0 % and 1.2 - 1.6 %, respectively, and are in the acceptable content in the case of Mg^{2+} (0.28 - 0.7 %). This deficiency in the concentration of alkaline cations is because by increasing the chemical activity of Al^{3+} in the soil solution, competition in the process of absorption and exchange of these nutrients, generating an imbalance in the Ca^{2+}/Al^{3+} and K^{+}/Al^{3+} ratios (Casierra-Posada and Aguilar-Avendaño, 2007). This process, together with the decrease in root density and functionality, alters the ionic transport mechanisms and cation uptake capacity, which generates nutritional imbalances in the seedlings (Hodson and Evans, 2020; Zhao and Shen, 2018). While Ca^{2+} deficiency affects processes such as energy metabolism, symplastic transport, cell wall, and membrane integrity, as well as resistance to diseases such as Fusarium spp. and Colletotrichum spp. (El Habbasha and Faten, 2015; Hao and Papadoupolus, 2004).

Foliar contents of micronutrients in African palm leaves

Foliar iron and manganese contents were higher than 80 and 160 mg kg^{-1} in the leaf tissues of all the EU, values higher than those reported by Munévar (2001) in E. guineensis palms. This fact is directly related to soil acidity since, in the initial conditions, the sample presented a pH of 4.6, which decreased as a function of adding aluminum, showing an extreme value of 2.98. In this sense, the solubility of iron and manganese is inversely proportional to the soil's acidity (Lindsay, 1979). In such a way that the solubility of iron-based compounds can increase by up to 1000 times per unit decrease in pH, while the solubility of manganese oxides can increase by up to 100 times per unit decrease in pH (Behera *et al*., 2015; Choudhury *et al*., 2021). This situation leads to excessive root uptake of iron and manganese cations, with subsequent translocation to leaf tissue, where oxidative stress, enzymatic alteration, and phytotoxicity processes are generated (Peng and Yamauchi, 1993).

Interaction between exchangeable acidity and edaphic and foliar variables

The results of PCA and Pearson's correlations between the increase in Al^{3+} content, edaphic and foliar variables allowed an understanding of the interaction between soil nutrients and the physiological behavior of the African palm crop when subjected to acidification in soils devoid of nutrient potential. In this sense, it is possible to observe that the principal components presented an opposite direction between the variables associated with soil acidities, such as aluminum content and exchangeable acidity, with the parameters affected by it, among which are biomass and leaf area, as well as the nutritional content of N, P, Ca^{2+}, Mg^{2+}, and K^{+}. This panorama ratifies the affectation in crop development in the face of Al^{3+} stress, derived from the adverse effects of the cation on fundamental biochemical and transport processes at the root level (Liu *et al*., 2008). These results show that the conditions of African oil palm cultivation in acid soils are a function of its tolerance to Al^{3+} saturation and the bioavailability of macro and micronutrients. For instance, under acidification conditions, it is essential to increase the application of calcium and magnesium to counteract the adverse effects of aluminum toxicity. Adjusting the nutritional plans to the crop requirements is crucial in these scenarios.

These results indicate that the growth and development of the African palm crop in acidic soils of the department of Córdoba-Colombia, and of all those areas of acidic soils to be planted with this crop, will be a function of its tolerance to Al^{3+} saturation and the genetics of the material to be planted, agronomic practices to reduce the amount of aluminum in soils, the bioavailability of macro and micronutrients in acidic soils, and fertilization practices. Therefore, this crop's tolerance to exchangeable aluminum and acidification does not mean obtaining high yields. On the contrary, in acidification conditions, it is essential to adjust the nutritional plans to the requirements of the crop, following nutritional demands and crop development stages.

CONCLUSION

The African oil palm (*Elaeis guineensis* Jacq.) is a crop of great commercial importance due to its high vegetable oil production capacity and ability to adapt to diverse soil and climatic conditions. These characteristics have made this crop an area of academic, governmental, and industrial interest as an economic development engine in tropical countries such as Colombia. In the case of Colombia, particularly in the northern part of the country, including the department of Córdoba, tropical soils tend to have a high acidity content. This acidity is associated with high rainfall and/or with the characteristics of the parent material that originated its formation, commonly related to high concentrations of exchangeable Al^{3+} in the soil solution, which adversely affects plants' root and meristematic cells.

Under this scenario, this research showed that increased Al^{3+} concentration in soil with acid characteristics (from Montelíbano, Córdoba) decreased soil reaction and increased exchangeable acidity. At the same time, an increase in aluminum concentration (3.5 cmolc kg^{-1} of Al^{3+}) resulted in a decrease in dry biomass and leaf area by 25.54 and 32.89 %, respectively. Concerning the nutritional content of N, P, Ca^{2+}, and K^{+}, a reduction of 6.41, 32.34, 28.84, and 16.2 %, was found when 3.5 cmolc kg^{-1} of Al^{3+} was added to the soil. These contents are considered deficient at the critical foliar levels for these nutritional elements in the African oil palm crop. The foliar iron and Mn^{2+} contents were found to be 190.5 and 60.5 %, respectively, above the critical levels and constituting potential phytotoxicity factors. In summary, the results of this research suggest that the African palm crop shows considerable tolerance to Al^{3+} saturation. However, it is planted in soils with low nutritional potential or with deficiencies of N, P, Ca^{2+}, Mg^{2+}, and K^{+}, and high contents of Al^{3+}, Fe^{3+}, and Mn^{2+} will cause damage to its development, viability, and profitability.

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