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RELATIONSHIP BETWEEN SOIL ACIDITY AND PRODUCTIVITY OF BANANA (*Musa* spp.) IN URABÁ, COLOMBIA

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ABSTRACT

Soil acidity plays an important role in the productivity of export bananas as it affects nutrient availability and phytotoxicity depending on soil pH. The objective of this research was to evaluate the relationship between soil pH and banana productivity in Uraba, Colombia. The study was conducted at the Ramiro Jaramillo Sossa experimental station, Banana Research Center (Cenibanano), Urabá, Antioquia. The sampling grid consisted of 110 points. Determination of pH was conducted *in situ*, and soil samples were processed in the laboratory using two solutions: distilled water and KCl. Significant differences were found between the solutions, aluminum extraction and field sampling. Additionally, the presence of Al^{3+} was confirmed in the pH range $H_2O \leq 5.5$. Finally, the pH values were pH KCl < pH H_2O < pH *in-situ*. The latter best explained the behavior of bunch weight, indicating that *in situ* determination of pH better reflects the real conditions of this variable, with a greater relationship with productivity.

Keywords: potential acidity, active acidity, exchangeable acidity, soil pH, bunch weight, bunch fingers, bunch hands, spatial correlation.

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INTRODUCTION

Banana is a widely cultivated and consumed fruit crop worldwide. Colombia exported 2.22 million tons in 2021, mostly produced in the Urabá Zone (62.79%) (Asociación de Bananeros de Colombia, 2022). The development and sustainability of crop productivity requires certain agro-climatological conditions, labor for the physicochemical conditioning of the soil and timely agronomic tasks. In this sense, soil acidity plays an important role its strong impact on the availability of nutrients, such as sulfur (S), phosphorus (P), molybdenum (Mo), and exchangeable bases, among others.

A pH<5.5 favors the reduction of oxidized forms of aluminum, manganese, and iron, resulting in high concentrations and, depending on susceptibility, phytotoxicity in plants (Osorio, 2018; Negese, 2019). Tropical soils generally have low pH values. In Colombia, it is estimated that between 80 and 85% of the soils are acid. In the Urabá Zone, the Banana Research Center (Cenibanano) (2022) used specialized soil health technicians to determine that approximately 52% of the evaluated area presents conditions between extremely acid and strongly acid (5.0 < ≤ 5.5).

Soil pH is determined by potentiometry using specialized equipment (potentiometers) with electrodes inserted directly into the soil suspension. This method evaluates the concentration of H^+ in the soil solution; this value is known as active acidity and is measured in a soil-water suspension at a 1:1 (weight/volume) ratio. However, some authors have reported that this value is usually unstable, and thus the use of electrolyte solutions presenting greater stability in the measurements, such as potassium chloride (KCl), is suggested. This condition is explained by the effect of factors such as seasonal behavior of precipitation, contribution of carbon dioxide (CO_2) by soil organisms and salinity changes throughout the year (Jaramillo, 2014; Delgado et al., 2019; Libohova et al., 2019; Khadka et al., 2021).

Measurements by suspending the soil in electrolyte solutions show lower pH values because of an increase in the displacement of H^+ and Al^{3+} ions from the exchange phase, as well as protons that are strongly bound to soil colloids in the non-exchangeable phase. This analysis refers to the potential acidity of the soil and is an indicator of the presence of aluminum. Aluminum significantly affects the growth of banana plants (Sancho and Molina, 2016; Zhang et al., 2019) because it interrupts the elongation and accumulation of biomass in the root system (Sánchez and Mira, 2013).

Al^{3+} is usually present when pH measurements in KCl are less than 5.2 (Kome et al., 2018; Nel et al., 2022)apparently the most routinely measured soil property is an important indicator of soil quality, serves as a guide for fertilizer recommendations and liming requirements, and is an index of biogeochemical processes in terrestrial ecosystems. This study was conducted to establish relationships among different pH measurements of surface soils (0–20 cm. Additionally, *in-situ* measurements are required to obtain accurate pH results. Sample pretreatment processes change the ionic activity (Elberling and Matthiesen, 2007 ; Nielsen et al., 2017; Ding et al., 2019) In addition, pH behavior can be affected by the variability of some soil properties such as moisture content and nutrient content, which are seasonal parameters that vary depending on climatic conditions and crop management (Yin et al., 2021). This research aimed to evaluate the relationship between soil pH and banana productivity in Urabá, Colombia. Determination was of pH was conducted *in* situ, and laboratory measurements were made using two solutions, distilled water and KCl.

MATERIALS AND METHODS

Description of the study area

The study was carried out in the Ramiro Jaramillo Sossa experimental station (32 ha) in the banana zone of Urabá (7.78026º N and 76.67294º W), municipality of Carepa, Antioquia, Colombia. The study area is located at 20 meters above sea level, with an average annual rainfall of 2961 mm and temperature of 27 °C (Instituto de Hidrología Meteorología y Estudios Ambientales (IDEAM), 2022), being classified as tropical humid dry forest [bh-T] (Jaramillo, 2014). There are four soil consociations: Fluventic Eutrodepts fine, Fluvaquentic Eutrodepts fine loamy to clayey, Vertic Endoaquepts fine loamy and Fluventic Eutrodepts fine loamy (Gutierrez and Romero, 2008). Banana plants cv. Williams are established at a planting density of 1650 plants ha^{-1}.

Sampling

The locations (x, y) of a sampling grid with 110 points distributed throughout the study area at a distance of 50 m x 50 m were determined with the QGIS geographic information system and the site polygon (Fig. 1). The coordinates of each point were exported with the Qfield application for mobile phones (QGIS Development Team, 2023).

In-situ determination of pH

At each monitoring point, 3 holes were made in the soil with an auger and then moistened with distilled water. pH was determined with a professional Groline HI98168 potentiometer

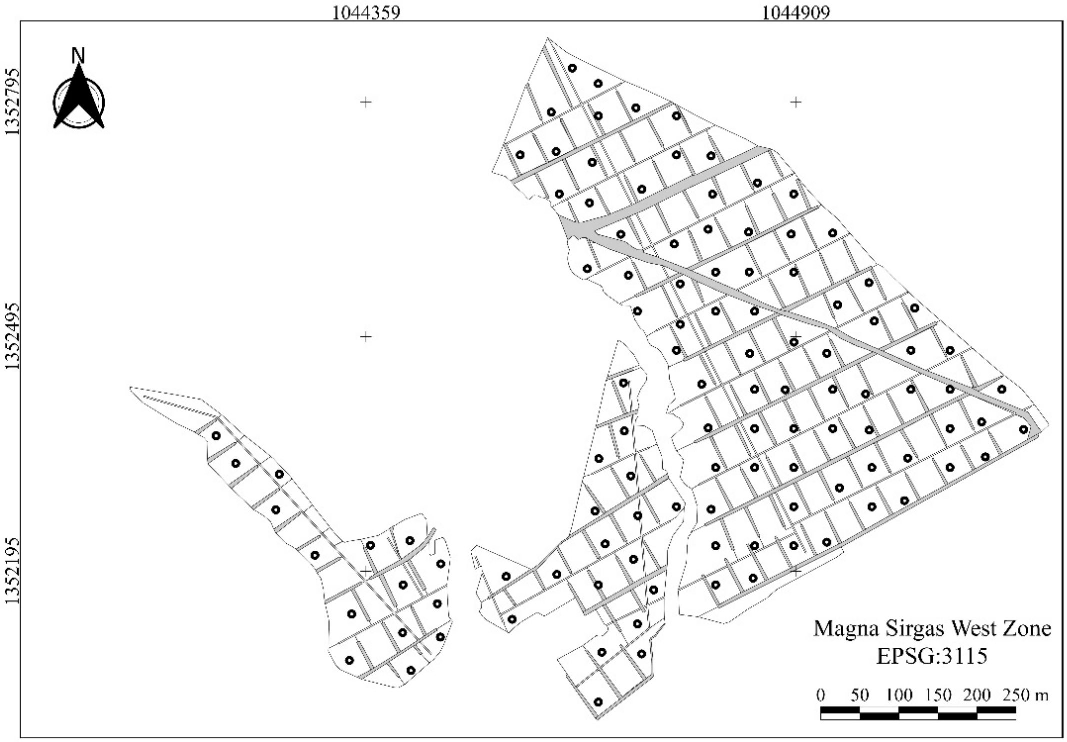

Fig. 1. Soil sampling grid, Ramiro Jaramillo Sossa experimental station, Carepa, Antioquia, Colombia.

for soils. Additionally, a sample of 500 g of soil was collected, packed, and transported to the laboratory of the Banana Research Center. The sampling was carried out in March 2022.

Determination of pH in the laboratory

The collected samples were pretreated following the NTC-ISO 11464 standard (Instituto Colombiano de Normas Técnicas [ICONTEC], 2022), which were dried in a greenhouse for 5 days, and then ground and passed through a 2-mm sieve. To determine pH, distilled water and KCl (1N) solutions were evaluated in proportions of 1:1 and 1:2 (soil:solution, w:v). Prior to pH determination, the suspensions were shaken with an orbital shaker (model SHKE2000, Thermo Scientific) at 185 rpm for one minute, left to stand for 30 minutes, and shaken again for one minute to determine the pH.

The following treatments were used for the analysis: Soil:water ratio 1:1 (T1); soil:water ratio 1:2 (T2); soil:saline solution (KCl [1N]) ratio 1:1 (T3); soil ratio:saline solution (KCl [1N]) 1:2 (T4) The *in-situ* pH determination was included as T5.

Texture. The method proposed by Bouyoucos (1936), which is based on Stokes's law, was used to determine soil texture. The concentration of suspended particles of clay and silt in a soil sample is measured, and the result taken to the textural triangle to find the texture (Jaramillo, 2014).

Exchangeable aluminum. The measurement of this variable was carried out according to the methodology proposed by Yuan (1959). Briefly, 10 g of previously treated soil were taken, 30 mL of KCl [1N] were added as an extraction medium, and the solution was shaken with an orbital shaker (model SHKE2000, Thermo Scientific) at 185 rpm for 30 min. The supernatant was decanted, and three drops of 0.1% phenolphthalein were added. A titration with NaOH [0.1N] was carried out until a pink coloration was obtained. Then, a drop of HCl [1N] was added. To make the solution colorless, once this state was obtained, 10 mL of NaF were added. If the pink color returned, titration with HCl [1N] was performed; otherwise, the sample did not present Al^{3+}.

Productivity. The productive units closest to the sampling point that presented fully emitted inflorescences at the time of soil sampling were marked and georeferenced. When the bunches reached harvest maturity (11 weeks later), they were harvested and transported to the packinghouse where weight (kg plant^{-1})

was evaluated with an electronic scale, and the number of hands and fingers was expressed in units.

Statistical Analysis

All univariate and spatial statistical analyses were carried out with R V4.1.2 software and programming environment (Gross and Ligges, 2015; Wickham, 2016; Fox and Weisberg, 2019; De Mendiburu, 2021; R Core Team, 2022).

Comparison of pH determination methods. The behavior of the pH determined *in situ* and in the laboratory in soil samples suspended in water and KCl in proportions of 1:1 and 1:2 was comparatively evaluated with a box and whisker graph. Additionally, given the non-normal distribution of the data, the Kruskal-Wallis test was applied to quantitatively validate the existence of differences between the methods. The differences between groups were evaluated using a Dunn's test with a confidence level of 95%.

Association of pH and productivity variables. The graphic and quantitative association was evaluated with Spearman's correlation coefficient, and the association of pH determined with different methods and productivity variables was also assessed. A principal component analysis (PCA) was also applied to determine the combined behavior of the pH determined with different methods and the productivity variables in components 1 and 2 (Wickham, 2016; Geladi and Linderholm, 2020; R Core Team, 2022)useful to separate systematic variation from noise. It allows to define a space of reduced dimensions that preserves the relevant information of the original data and allows visualization of objects (scores.

Spatial analysis. The spatial behavior of the pH determined *in situ* was evaluated with empirical variogram, which presented a sill of 0.024, a range of 240 m, and a nugget effect of 0.016 using a fourth grade polynomial ($a + b * x + c * x^2 + d * x^3 + e * x^4$). These characteristics were entered as parameters in the ordinary kriging interpolation method for predictions on a grid of points with a cell size of 0.1 x 0.1 m for mean unknown, stationary and isotropic processes. The spatial dependence is represented by the nugget/sill ratio value based on the classification presented by Cambardella et al. (1994), where ratios ≤25% are strongly spatially dependent; 25-75% moderately spatially dependent; and >75% weakly spatially dependent. The interpolated pH raster was classified in the following categories: extremely acid (3.5 - 4.5); very strongly acid (4.5 - 5.0); strongly acid (5.0 - 5.5); moderately acid (6.0 - 6.5); slightly acid (6.0 - 6.5); neutral (6.5 - 7.3); and slightly alkaline (7.3 - 7.8). Kriging was done with SAGA version 2.3.1, and reclassifications were done with QGIS version 3.14.16 (Conrad et al., 2015; QGIS Development Team, 2023).

RESULTS AND DISCUSSION

Fig. 2 shows the box and whisker plot of the soil pH behavior evaluated directly in the field and in the laboratory suspended in distilled water and KCl with different soil:solution ratios (weight: volume). The greatest variability occurred when the pH determinations were made *in situ*. On the contrary, the behavior was more adjusted around the median when the evaluations were carried out in the laboratory with the two solutions. However, when suspended in KCl, some low, extreme values were detected with water at a ratio (1:1), some of which were maximum. The Kruskal-Wallis test with 95% confidence showed that there were no significant differences in the pH value determined with the same solution with the two proportions evaluated under laboratory conditions. On the other hand, there were differences between solutions and even with the *in situ* determination. The highest pH values, around 6.23, were obtained when the soil was suspended in distilled water, while those determined *in situ* were significantly lower (around 5.99) and were much lower (around 4.55) when they were suspended in KCl (1N).

The behavior of the pH determined in water in the two proportions was as expected, since when soil is suspended in a larger volume of water, the pH tends to increase because some H_3O^+ protons can pass from the solution to the exchange zone. In this case, however, this was not significant. On the contrary, the addition of KCl favors H_3O^+ cations in the saturation zone of the colloid that are displaced by K^+ and pass into the soil solution, causing the pH to drop (Fig. 2) (Kome et al., 2018; Yerima et al., 2020; Khadka et al., 2021)"ISSN":"05872596","abstract":"Soil pH is most routinely measured parameter among all others in soil chemistry laboratory. There are various methods developed for pH measurement, although we using only distilled water from the beginning. In Nepal, there do not have database for showing performance of the methods. The three methods namely; H2O, KCl and CaCl2 with their soil:solution ratios (1:1, 1:2 and 1:2.5. For *in-situ* measurements, although the values were close to the determinations made with water in the laboratory, the greater variability reflected the lesser control over soil moisture during determinations. Furthermore, it is an interesting indicator of what is happening *in situ* with acidity while being monitored.

Fig. 3 shows main components one and two

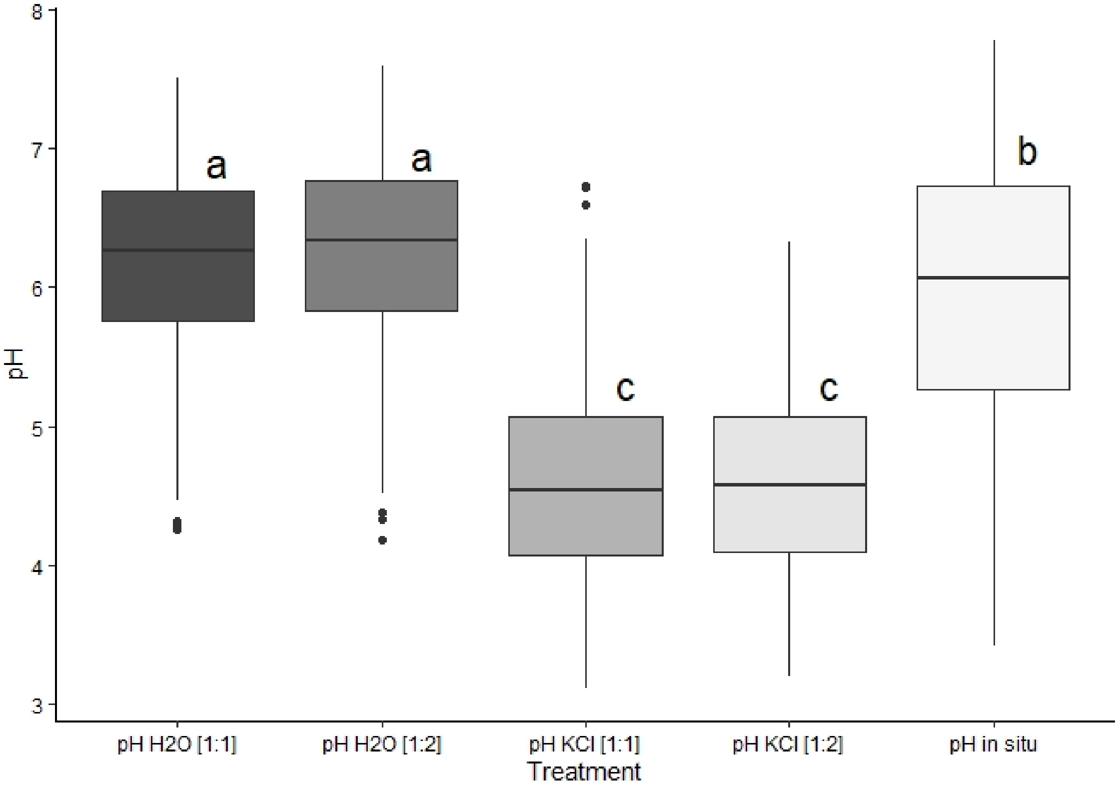

Fig. 2. Behavior of the pH determined in the field and in the laboratory for the soil suspended in distilled water and KCl (1N) in proportions 1:1 and 1:2. Different letters denote significant differences between dissolution ratios using the Dunn test (p-value ≤0.05).

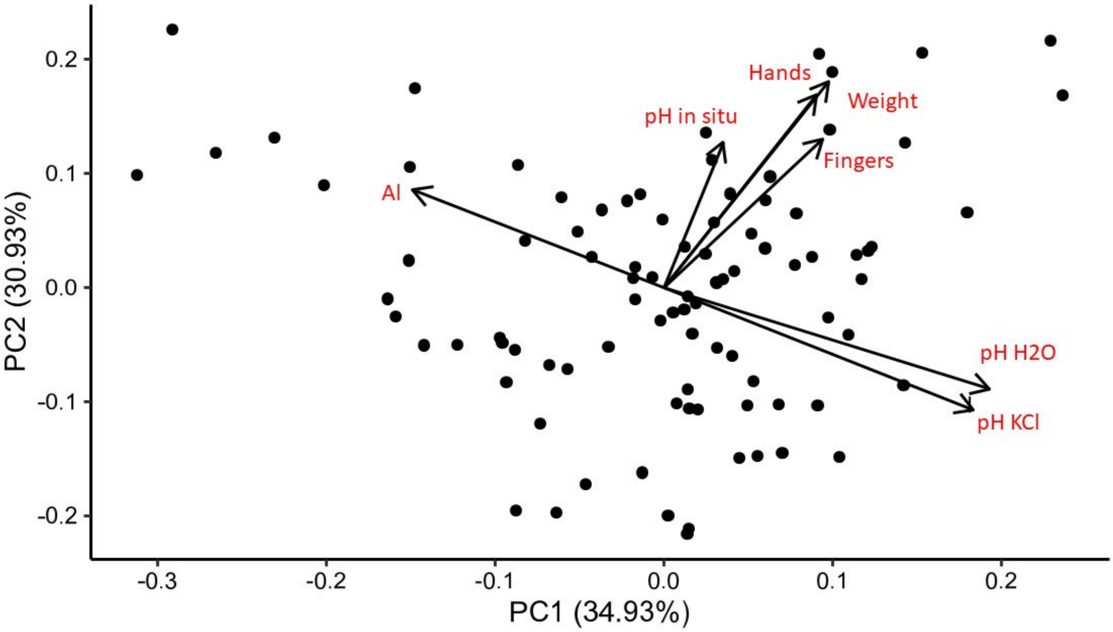

Fig. 3. Principal components 1 and 2 for the soil pH variables determined in water and KCl in a 1:1 w:v ratio and those determined *in situ*, and productivity variables.

for the productivity variables and the soil pH determined in water and KCl at a 1:1 ratio, as well as evaluated *in situ*. The two components explained 65.86% of the total variability, evidencing two groups of association of variables. The first group included the variables pH determined in water and in KCl under laboratory conditions, which were inversely related to the Al content in the soil. The second group included the productivity variables (bunch weight, number of fingers and hands) and pH determined *in situ*. The relationship between the two groups of variables was low. The strong relationship between the pH determined in water and that determined in KCl was corroborated by the high correlation values (Table 1), as well as the graphic association shown in Fig. 3. Similarly, the correlations between the pH determined *in situ* and productivity variables were significant in terms of bunch weight and, to a lesser extent, number of fingers (Table 1).

Although determinations of the pH in water and KCl(1N) adequately express the concentration of H_3O^+ cations in a soil solution and in the exchange zone, respectively, they do not seem to adequately reflect the behavior of the factors in the field at a given moment; they control the bidirectional and reversible flow between these two phases of the soil, as reflected in the *in-situ* evaluations. This may be due to the fact that the sample pretreatments carried out in the laboratory (drying, grinding and sieving) standardize the size of the particles and soil moisture, allowing suspensions to be made with very precise soil:solution ratios that are rarely achieved in the field because of fluctuations in terms of environment, micro-topography, and granulometry, among other factors (Nielsen et al., 2017; Ding et al., 2019; Farinango-Guzman et al., 2020).

The ratio between the nugget and the sill is 66.67%, which is classified as a moderately spatially dependent, indicating that the pH depends moderately on the sampling site (Cambardella et al., 1994; Terefe et al., 2021; Kar et al., 2023). The moderate correlations can be influenced by internal factors like parental material of the soil, texture, organisms and microbial respiration, decomposition of organic material and vegetation covers, as well as by external factors like fertilization and management practices (Terefe et al., 2021; Yin et al., 2021; Corréa et al., 2022; Kumar et al., 2022).

There was a structured behavior with clearly defined sectors that varied from very strongly acidic to neutral (Table 2), suggesting broad variability (Fig. 4). The sectors with neutral pH (19.63%) were located towards the southwestern part of the study area. The sectors with slightly acidic pH (23.35%) tend to be distributed in the south-north direction and centrally in the east-west direction. This behavior was similar for the moderately acid category (34.08%). The pH in

Table 1. Spearman correlation of variables.

	pH H_2O	pH KCl	pH *in situ*	Al	Weight	Hands	Fingers
pH H_2O	1	0.923***	0.001	-0.599***	0.023	0.037	0.147
pH KCl		1	-0.131	-0.609***	-0.059	0.016	0.095
pH *in situ*			1	0.106	0.400***	0.177	0.249*
Al				1	0.009	-0.046	-0.148
Weight					1	0.698***	0.366***
Hands						1	0.373***
Fingers							1

*p-value< 0.05, ** p-value < 0.01 and *** p-value < 0.001.

Table 2. Distribution of variables.

pH Category	Range	% Area	% Bunches	% Sampling points
Very Strongly Acid	4.5 – 5.0	2.03	2.78	2.73
Strongly Acid	5.0 – 5.5	20.89	25.04	22.73
Moderately Acid	5.5 – 6.0	34.08	27.53	30.91
Slightly Acid	6.0 – 6.5	23.35	22.11	25.45
Neutral	6.5 – 7.3	19.63	22.55	18.18
n		32.97 ha	683 bunches	110 points

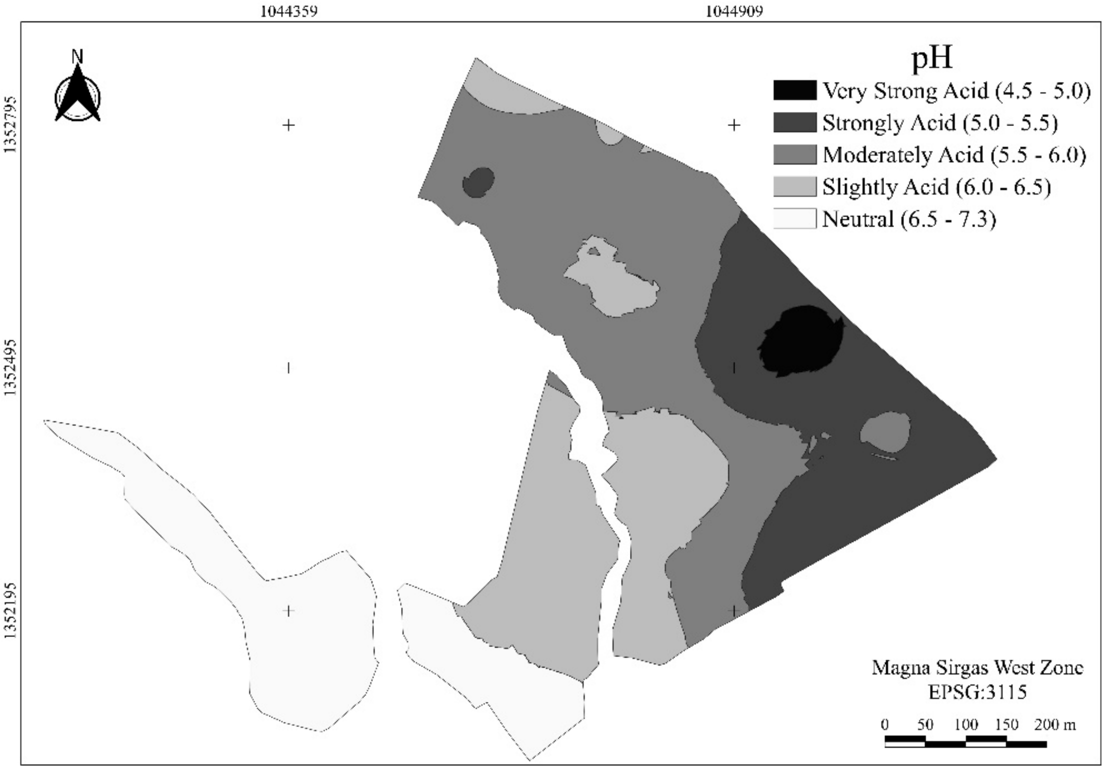

Fig. 4. Spatial distribution of *in-situ* pH categories in the study area, Carepa, Antioquia, Colombia.

the strongly acid category (20.89%) was in the southeastern part of the study area, while the very strongly acid category was in the southeastern section (2.03%).

Based on the previous results, 57.43% of the area had moderately acidic or slightly acidic conditions, which is optimal for banana cultivation because good absorption of nutrients such as calcium (Ca), nitrogen (N), and potassium (K) is favored, and the presence of manganese (Mn) does not cause phytotoxicity (Osorio, 2018). On the other hand, 22.93% of the study site had pH values ≤ 5.5 where the generation of Al^{3+} was favored, which can directly cause phytotoxicity in plants, along with acidity conditions that affect the absorption of nutrients (Jaramillo, 2014; Osorio, 2018). However, no statistical differences (p-value>0.05) were found in the productivity variables with the Al^{3+} content during the evaluations.

Table 3 shows the equations for the spatial correlation of productivity variables with the *in-situ* pH measurements.

The distribution of the *in-situ* pH explained 28.41 to 55.45% of the distribution of the evaluated productive variables, which confirmed the spatial dependence of crop productivity on soil pH. This agrees with Sanches et al. (2019), who conducted a study in Brazil and found that pH is an important attribute that directly impacts the productive potential of crops spatially. On the other hand, Rodrigues et al. (2012) found that the distribution pattern of soil properties explains 65% of maize productivity distribution. In summary, pH affects the bioavailability of nutrients such as nitrogen (N), copper (Cu), and potassium (K), elements that, when deficient in the soil, affect the number of fingers and the quality in banana bunches (Soto, 2015). Shukla et al. (2022) indicated that an increase in the number of fingers can occur as a result of an increase in the availability of N in the soil and its translocation to the plants.

Fig. 5 shows the behavior of bunch weight in relation to the acidity categories. In general terms, higher weights are obtained for the acidity categories between 5.5 and 7.3; however, it was optimal for 6.0 to 6.5. The weights in the categories at pH<5.5 were significantly lower. If the behavior of bunch weight in categories 3-5, 4.5-5, 5.0-5.5 of pH is compared with the behavior of Al in the same categories, an inverse behavior is observed, which could confirm the negative effect of pH on productivity. When soil has acidity ranges with pH ≤ 5.5, the growth of different crops is affected.

Table 3. Spatial correlation of the productivity variables depending on *in-situ* pH.

Parameter	Equation	R² (%)	p-value
Bunch Weight	$y = 0.17x^3 - 1.64x^2 + 3.38x + 23.89$	28.41	$2.2e^{-16}$
Hands	$y = 0.0028x^3 + 6.45$	39.99	$2.2e^{-16}$
Fingers	$y = 0.078x^3 - 0.90x^2 + 3.17x + 16.19$	55.45	$2.2e^{-16}$

x= pH *in-situ*, y= Parameter.

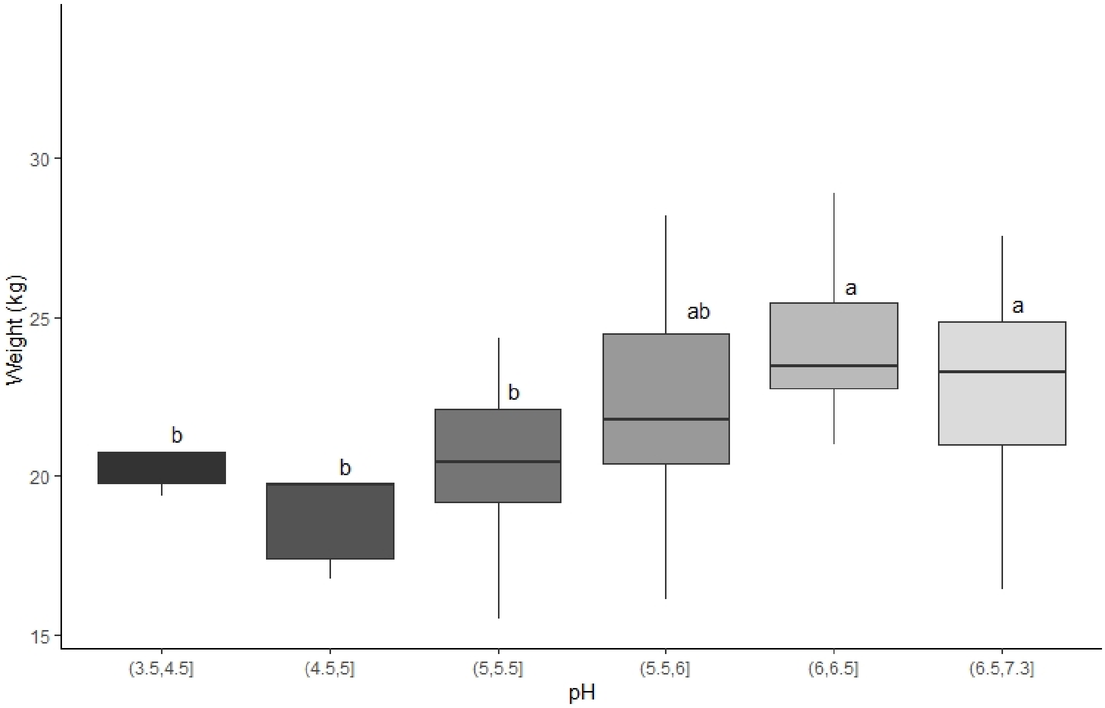

Fig. 5. Distribution of bunch weight according to the categories of pH evaluated *in situ*. Different letters denote significant differences according to the Dunn test, p-value<0.05.

This situation occurs because of an increase in the concentrations of Al and Mn and deficiencies of some minerals such as S, N, P, and K (Golla, 2019) causes, extent and management practices. Soil acidity is the problem of agricultural activities in Ethiopian highlands (cultivated lands. Soto (2015) reported that higher doses of N in the soil tend to increase bunch weight, resulting from an increase in the degree of fingers and number of fingers. N begins to decrease solubility in the soil at pH ≤ 5.5 (Jaramillo, 2014). On the other hand, Lahav and Israeli (2019) and Soto (2015) observed that K deficiencies in the soil can cause weight loss in banana bunches, specifically affecting the length and diameter of the fingers. For ranges of 6 < pH ≤ 7.3, there is adequate availability of most minerals (Jaramillo, 2014; Golla, 2019) causes, extent and management practices. Soil acidity is the problem of agricultural activities in Ethiopian highlands (cultivated lands, which may indicate good plant nutrition and consequently higher cluster weights. Leiva Soto et al. (2022) trophic level and habitat use of three sympatric stingrays; Hypanus guttatus, H. marianae and H. berthalutzae through combined stomach content and stable isotope (δ13C and δ15N found a trend of increased productivity in crops such as soybean and corn when the pH increased to values of 7.

No statistical differences were found in the *in-situ* pH measurements in terms of number of fingers (p-value=0.305) and the mean value obtained during the study was 20 fingers; this behavior was also observed in the number of hands (p-value=0.36) with a mean value of 7 hands per bunch. This may have been due to the quality policies in place at the site since they remove hands and fingers from bunches to standardize quality and size characteristics (Vargas et al., 2017; Vargas et al., 2019).

CONCLUSIONS

The pH determined with soil suspended in water presented significantly higher values for the suspension in KCl. However, no significant differences were found between water and KCl in the dilution of the soil suspension from a ratio of 1:1 to 1:2 with a slightly increased pH. The pH determined *in situ* presented greater variability. Principal components 1 and 2 and their correlation produced two groups of variable association: the first related to the aluminum content with the pH determined in the laboratory when suspended in water or KCl. The other group associated the productivity variables with the pH determined *in situ*. The spatial behavior of the *in-situ* pH was structured, defining the pH categories, which generated significant differences for the bunch weight variable. Finally, it was concluded that the pH determined *in situ* seemed to better reflect the real conditions of this variable, which generated a stronger relationship with productivity.

LITERATURE CITED

Asociación de Bananeros de Colombia. 2022. Coyuntura Bananera de Colombia 2021. Available online at: https://augura.com.co/wp-content/uploads/2022/04/COYUNTURA-BANANERA-2021.pdf

Boruvka, L., L. Mladkova, and O. Drabek. 2005. Factors controlling spatial distribution of soil acidification and Al forms in forest soils. Journal of Inorganic Biochemistry 99(9):1796–1806. https://doi.org/10.1016/j.jinorgbio.2005.06.028

Bouyoucos, G. 1936. Directions for making mechanical analyses of soils by the hydrometer method. Soil Science 42(3):225–230. https://ui.adsabs.harvard.edu/link_gateway/1936SoilS..42..225B/doi:10.1097/00010694-193609000-00007

Cambardella, C.A., T.B. Moorman, J.M. Novak, T.B. Parkin, D.L. Karlen, R.F. Turco, and A.E. Konopka. 1994. Field-scale variability of soil properties in Central Iowa soils. Soil Science Society of America Journal 58(5):1501–1511. https://doi.org/10.2136/sssaj1994.03615995005800050033x

Chauhan, D.K., V. Yadav, M. Vaculík, W. Gassmann, S. Pike, N. Arif, et al. 2021. Aluminum toxicity and aluminum stress-induced physiological tolerance responses in higher plants. Critical Reviews in Biotechnology, Taylor & Francis 41(5):715–730. https://doi.org/10.1080/07388551.2021.1874282

Conrad, O., B. Bechtel, M. Bock, H. Dietrich, E. Fischer, L. Gerlitz, et al. 2015. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geoscientific Model Development 8(7):1991–2007. https://doi.org/10.5194/gmd-8-1991-2015

Corréa, M.F., G.I. Gadotti, R. de M. Pinheiro, A.P. Nadal, R. de O. Vergara, R. Navroski, et al. 2022. Variabilidade espacial do solo em produção de sementes de soja e seus componentes do rendimento. Diversitas Journal 7(2):542–554. https://www.diversitasjournal.com.br/diversitas_journal/article/download/2058/1630/12079

Delgado, J., J. Valdez, and F. Incio. 2019. Influencia de la dilución y concentración de los electrolitos en la medición del pH en suelos ácidos. Revista Científica Pakamuros 7(2):13–21. https://doi.org/10.37787/pakamuros-unj.v7i2.89

Ding, C., S. Du, Y. Ma, X. Li, T. Zhang, and X. Wang. 2019. Changes in the pH of paddy soils after flooding and drainage: Modeling and validation. Geoderma 337:511–513. https://doi.org/10.1016/j.geoderma.2018.10.012

Eduah, J.O., E.K. Nartey, M.K. Abekoe, S.K., Asomaning, J.K. Essibu, and S.W. Henriksen. 2022. Acidity and aluminum speciation in biochar amended tropical soils. Communications in Soil Science and Plant Analysis, Taylor & Francis 53(7):913–927. https://doi.org/10.1080/00103624.2022.2034847

Elberling, B., and H. Matthiesen. 2007. Methodologically controlled variations in laboratory and field pH measurements in waterlogged soils. European Journal of Soil Science 58(1):207–214. http://dx.doi.org/10.1111/j.1365-2389.2006.00828.x

Farinango-Guzman, W., B. Ulcuango, O. Gualavisí, D. Reinoso, G. Espinosa, and L. Andrade. 2020. Evaluación de la variabilidad de cuatro propiedades del suelo al incorporar dosfuentes de compost a tres dosis. Pol. Con. (Edición núm. 42) 5(2):860–882. https://dialnet.unirioja.es/servlet/articulo?codigo=7435309

Fox, J., and S. Weisberg. 2019. An R Companion to Applied Regression. Sage Publications.

Geladi, P., and J. Linderholm. 2020. 2.03 - Principal Component Analysis☆. In Brown, S., Tauler, R. and Walczak, B. (Eds.). Comprehensive Chemometrics (Second Edition). Elsevier, Oxford. https://doi.org/10.1016/B978-0-12-409547-2.14892-9

Golla, A. 2019. Soil Acidity and its Management Options in Ethiopia: A Review. International Journal of Scientific Research and Management 7(11):1429–1440. https://doi.org/10.18535/ijsrm/v7i11.em01

Gross, J. and U. Ligges. 2015. Nortest: Tests for normality. R package Version 1.0-4.

Gutierrez, J., and M. Romero. 2008. Aplicaciones de los estudios de suelo en la agricultura, Ciencias Ambientales e Ingeniería, Banatura, Medellín. Available online at: https://repository.agrosavia.co/bitstream/handle/20.500.12324/19412/45013_60764.pdf?sequence=1&isAllowed=y

Instituto Colombiano de Normas Técnicas. 2022. Gestión Ambiental. Calidad del suelo. pretratamiento de las muestras de suelo para análisis fisicoquímicos. (NTC ISO 11464), No. 11464. Available online at: https://es.scribd.com/document/390143796/NTC-ISO-11464#

Instituto de Hidrología Meteorología y Estudios Ambientales (IDEAM). 2022. Promedios climatológicos. Available online at: www.ideam.gov.co/web/tiempo-y-clima/clima

Jaramillo, D.F. 2014. El Suelo: Origen, propiedades, espacialidad. 2nd ed., Editorial Universidad Nacional de Colombia, Sede Medellín, Medellín.

Kar, G., P.K. Patra, and A.K. Singh. 2023. Spatial variability of soil organic carbon, pH and electrical conductivity and its influencing factors in a watershed of Coastal Region of Odisha, India. Communications in Soil Science and Plant Analysis, Taylor & Francis 54(14): 2031–2044. https://doi.org/10.1080/00103624.2023.2211114

Khadka, D., R. Amgain, S. Joshi, and S. Shrestha. 2021. Evaluation of distilled water pH measurement with electrolyte methods in cultivated soils of Nepal. Agrochemistry and Soil Science 92:52–61, doi: 10.31073/acss92-06.

Kome, G.K., R.K. Enang, B.P.K. Yerima, and M.G.R. Lontsi. 2018. Models relating soil pH measurements in H_2O, KCl and $CaCl_2$ for volcanic ash soils of Cameroon. Geoderma Regional 14(1): e00185. https://doi.org/10.1016/j.geodrs.2018.e00185

Kumar, P., P. Kumar, M. Sharma, A.K. Shukla, and N.P. Butail. 2022. Spatial variability of soil nutrients in apple orchards and agricultural areas in Kinnaur region of cold desert, Trans-Himalaya, India. Environmental Monitoring and Assessment, Springer International Publishing 194(4):290. https://doi.org/10.1007/s10661-022-09936-3

Lahav, E., and Y. Israeli. 2019. Mineral deficiencies of banana. In Jones, D. (Ed.). Handbook of Diseases of Banana, Abac and Enset, CABI, Boston.

Leiva Soto, A., S.W. Culman, C. Herms, C. Sprunger, and D. Doohan. 2022. Managing soil acidity vs. soil Ca:Mg ratio: What is more important for crop productivity? Crop, Forage & Turfgrass Management 9 (1): 1–10. https://doi.org/10.1002/cft2.20210

Libohova, Z., C. Seybold, K. Adhikari, S. Wills, D. Beaudette, and S. Peaslee. 2019. The anatomy of uncertainty for soil pH measurements and predictions: Implications for modellers and practitioners. European Journal of Soil Science 70(1):185–199. https://doi.org/10.1111/ejss.12770

De Mendiburu, F. 2021. Agricolae: Statistical Procedures for Agricultural Research. Package 'Agricolae'. https://cran.r-project.org/web/packages/agricolae/agricolae.pdf

Negese, W. 2019. Review on the extent of acid soil in Ethiopia, its impact and management methods. Journal of Biology, Agriculture and Healthcare 9(15):22-27. http://doi.org/10.7176/JBAH/9-17-04

Nel, T., A.G Hardie, and C.E. Clarke. 2022. Simple and multivariate linear regression models for pH conversion between measurement techniques. Communications in Soil Science and Plant Analysis, Taylor & Francis 53(14):1797–1808. https://doi.org/10.1080/00103624.2022.2063324

Nielsen, K.E., A. Irizar, L.P. Nielsen, S.M. Kristiansen, C. Damgaard, M. Holmstrup, A.R. Petersen. 2017. *In situ* measurements reveal extremely low pH in soil. Soil Biology and Biochemistry 115: 63–65. https://doi.org/10.1016/j.soilbio.2017.08.003

Osorio, W. 2018. Manejo de Nutrientes En Suelos Del Tropico, 3rd ed., L. Vieco, Medellín, Colombia.

QGIS Development Team. 2023. QGIS. QGIS Association.

R Core Team. 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, R Foundation for Statistical Computing, Vienna.

Rodrigues, M.S., J.E. Corá, and C. Fernandes. 2012. Soil sampling intensity and spatial distribution pattern of soils attributes and corn yield in no-tillage system. Engenharia Agricola 32(5):852–865. https://doi.org/10.1590/S0100-69162012000500005

Sanches, G.M., P.S. Graziano Magalhães, and H.C. Junqueira Franco. 2019. Site-specific assessment of spatial and temporal variability of sugarcane yield related to soil attributes. Geoderma 334: 90–98. https://doi.org/10.1016/j.geoderma.2018.07.051

Sánchez, J., and J. Mira. 2013. Principios para la nutrición del cultivo de banano. 1st ed., Augura, Medellín, Colombia.

Sancho, H., and E. Molina. 2016. Efecto del Mg y pH en la reducción de la toxicidad de Al en plantas de banano cultivadas en solución hidropónica. Siembra 3(1):53–66. https://doi.org/10.29166/siembra.v3i1.260

Shukla, A., A.K. Dwivedi, V.K. Tripathi, and R.S. Singh. 2022. Effect of INM on yield parameters of tissue cultured banana CV. Grand Naine under north Indian condition. The Pharma Innovation Journal 11(4):1334–1336. https://www.thepharmajournal.com/archives/2022/vol11issue4/PartS/11-4-222-591.pdf

Soto, M. 2015. Bananos 2: Tecnologías de producción. 1st ed., Editorial Tecnológica de Costa Rica. Cartago, Costa Rica.

Terefe, R., K. Yu, Y. Deng, X. Yao, F. Wang, and J. Liu. 2021. Spatial variability of soil chemical properties of Moso bamboo forests of China. Journal of Forestry Research 32(6):2599–2608. https://doi.org/10.1007/s11676-020-01251-2

Vargas, A., M. Madrigal, P. Calvo, and M. Saenz. 2019. Efecto de la desflora y del desmane en la producción de banano Dátil (Musa AA). Corbana 45(65):93–106. https://www.musalit.org/seeMore.php?id=19583

Vargas, A., W. Watler, M. Morales, and R. Vignola. 2017. Prácticas efectivas para la reducción de impactos por eventos climáticos en el cultivo de banano en Costa Rica. Catie. http://www.mag.go.cr/bibliotecavirtual/F01-8205.pdf

Wickham, H. 2016. Ggplot2: Elegant Graphics for Data Analysis, Springer-Verlag. New York, USA.

Yerima, B.P.K., R.K. Enang, G.K. Kome, and E. Van Ranst. 2020. Exchangeable aluminium and acidity in acrisols and ferralsols of the north-west highlands of Cameroon. Geoderma Regional 23: e00343. https://doi.org/10.1016/j.geodrs.2020.e00343

Yin, H., B. Marellin, X. Zeng, A. Mason, and C. Cao. 2021. Soil sensors and plant wearables for smart and precision agriculture. Advanced Materials 33(20):1–24. https://doi.org/10.1002/adma.202007764

Yuan, T. 1959. Determination of exchangeable hydrogen in soils by a titration method. Soil Science 88(3):164–167. http://doi.org/10.1097/00010694-195988030-00008

Zapata, R. 2022. Los procesos químicos del suelo. Centro Editorial de la Facultad de Ciencias, 1st ed., Universidad Nacional de Colombia. Medellín, Colombia.

Zhang, J., S. Bei, B. Li, J. Zhang, P. Christie, and X. Li. 2019. Organic fertilizer, but not heavy liming, enhances banana biomass, increases soil organic carbon and modifies soil microbiota. Applied Soil Ecology 136:67–79. https://doi.org/10.1016/j.apsoil.2018.12.017