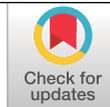# AN APPROACH FOR PREDICTING PHOSPHORUS REQUIREMENT FOR COFFEE IN SOILS OF THE COLOMBIAN COFFEE ZONE

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Coffee crop demands phosphorus (P) during the nursery stage and vegetative growth. These requirements are commonly satisfied by applying a high dose of soluble phosphatic fertilizers, which increases production costs and causes environmental concerns. The Colombian coffee zone has a great diversity of soils with variable mineral composition and organic matter (OM) content. These conditions exhibit a long-term stability, concomitantly govern soil P availability and, hence, a standard recommendation for P fertilization may cause nutritional imbalance in the soil solution. To accurately estimate soil P-availability in Colombian coffee soils, a P-fixation (PF)-based approach using sorption isotherms technique was evaluated in five Andisols and four Inceptisols. Changes in the soil solution P concentration were monitored over time. Results showed that PF value was overestimated (> 68 %) during 36 h of equilibration; after this period, the system stabilized, providing reliable PF values. The relation between PF and applied P was assessed at a concentration of 0.2 mg L^{-1} ($P_{0.2}$), level considered adequate in the soil solution to support maximal crop yields in different cultivated plants, was achieved by applications between 104 and 773 mg kg^{-1} of P in Andisols, and between 0 and 349 mg kg^{-1} of P in Inceptisols. OM content (OM: 7.7%), presence of non-crystalline materials, texture, and mineralogy explained the PF across soils. These finding suggest that a PF-based approach could serve as a valuable tool for developing site-specific P fertilization strategies and useful for establishing future P coffee fertilization in Colombia.

Keywords: soil-organic matter, equilibration time, non-crystalline materials, $P_{0.2}$ value, texture.

UN ENFOQUE PARA PREDECIR EL REQUERIMIENTO DE FÓSFORO PARA EL CAFÉ EN LOS SUELOS DE LA ZONA CAFETERA DE COLOMBIA

El café demanda fósforo (P) durante la fase de vivero y crecimiento vegetativo. Dichos requerimientos comúnmente se satisfacen con fertilizantes fosfóricos solubles, incrementando los costos de producción y causando problemas medioambientales. La zona cafetera colombiana es diversa en suelos, con variabilidad en su composición mineralógica y contenidos de materia orgánica (MO). Estas condiciones son estables en el tiempo y conjuntamente gobiernan la disponibilidad de P. Por consiguiente, una recomendación estándar de fertilización fosfórica puede causar desbalances nutricionales en la solución de suelo. Para estimar con precisión la disponibilidad de P en los suelos de la zona cafetera colombiana, se evaluó la fijación de P (PF) mediante la técnica de isotermas de adsorción en cinco Andisoles y cuatro Inceptisoles. Cambios del P en la solución del suelo fueron monitoreados en el tiempo. PF estuvo sobreestimada (> 68%) durante 36 h de equilibrio; luego, el sistema se estabilizó generando valores confiables. La relación entre PF y el P aplicado para alcanzar $P_{0.2}$ en solución, el cual corresponde a la concentración de P para el máximo rendimiento en diferentes cultivos, se alcanzó suministrando 104-773 mg kg^{-1} de P en Andisoles y 0-349 mg kg^{-1} de P en Inceptisoles. La MO (MO: 7.7%), los materiales no cristalinos, la textura y la mineralogía explicaron la PF. Los resultados sugieren que un enfoque basado en PF representa una herramienta para la fertilización fosfórica específica según el tipo de suelo y es útil para desarrollar futuros programas de fertilización con P para el café en Colombia.

Palabras clave: Materia orgánica del suelo, tiempo de equilibrio, materiales no cristalinos, nivel $P_{0.2}$, textura.

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Phosphorus (P) is a key nutrient for crops production (Helin & Weikard, 2019; Zhu et al., 2018). In coffee, it is required mainly during the nursery and vegetative growth stages (Ávila et al. 2007; Sadeghian & González, 2012), even though during reproductive growth stage coffee plants have low P requirement in comparison with other nutrients (González-Osorio et al. 2023). Phosphoric fertilizers prices will remain volatile (INN, 2022) in a market where supply and demand are tight (Alewell et al. 2020). Under these conditions, strategies for an effective use of P are necessary. In many cases P fertilization in coffee crops is based on general criteria, often without considering the available P levels in the soil (Minten et al., 2017). Currently, a general recommendation for P fertilization for coffee seedlings in nursery stage is being used of 2 to 4 g diammonium phosphate per kg of soil. However, there is a high uncertainty about the real benefits derived from this practice (Díaz et al., 2008). It is hypothesized that in some soils this P fertilization may be unnecessary and in other cases it may be insufficient to satisfy P coffee requirements (González-Osorio et al. 2025).

Different approaches have been developed to understand P dynamics in the soil-plant system (Bindraban et al. 2020; Yan et al., 2017, Bhattacharyya et al., 2015; Gauthman & Prabhakar, 2012). Taking into account that the phosphate ions ($H_2PO_4^-$) reach the plant root surface by diffusion, the P availability quantification should consider the presence of phosphate in both solid and liquid phases (Dijkstra et al., 2016).

Under the variable soil conditions of Colombia, Bray II is a traditional soil test widely used, to estimate P available, however, the time of extraction through this methodology is limited, thereby a reaction above 40 s, could dissolve and desorb P forms not available, like P strongly adsorbed (in Andisols) or P-precipitation with Fe, Ca or Al; generating overestimation of P available (Osorio, 2014). Under these considerations, is necessary a better bioavailability indicator to predict the need of P application (Hue & Fox, 2010). The isotherms of P sorption have been largely used to determine soil capacity to adsorb P ions and/ or to evaluate soil PF on its colloids (Fox & Kamprath, 1970). In this method, after soluble phosphate is applied, a fraction is adsorbed and another part remains in solution, due to both fractions reach a physical-chemical equilibrium after a few days, when the soluble P fraction is measured inherently, the adsorbed P can be quantified as well (Tokura et al. 2020).

Correlation and calibration are essential parts of an effective soil testing methodology (Soratto & Sandaña, 2020; Braun et al., 2019; Wang et al., 2019). The isotherm equilibrium approach can be used to correlate the level of P added to the soil solution with P concentration. In addition, the calibration requires an evaluation in plants in both greenhouse and field conditions to determine plant P uptake. Several studies have been conducted using this technique in different plant species. For instance, maximal yields of sugarcane (*ca*. 90%) are achieved when soluble P concentration is 0.1 mg L^{-1}, 0.05 mg L^{-1} in yucca, 0.3 mg L^{-1} in lettuce and 0.17 mg L^{-1} in potato, among others (Hue & Fox, 2010). Also, it has been widely reported that the highest mycorrhizal effectiveness of diverse plant species (coffee, avocado, papaya, leucaena, passion fruit, etc.) is reached when soluble P fraction (measured with soil P sorption isotherm) is around 0.02 and 0.2 mg L^{-1} (González-Osorio et al. 2022, Osorio & Habte, 2015, Habte & Bittenbender, 1999).

The Colombian coffee growing zone has great diversity of soils as a result of the interactions of different soil genesis factors, with different soil organic matter (SOM) types

and contents, mineral composition, chemical reaction, etc. (González et al. 2009). These soil conditions concomitantly govern soil P availability (Fink et al. 2016). Therefore, a method to determine crop P requirement that take into consideration these soil factors, particularly PF and soil P adsorption capacity, becomes relevant since it can contribute to improving effectiveness in P management, reducing production costs and preventing environmental problems derived from excessive P fertilization.

Based on the last considerations this study was aimed to evaluate PF through the P-sorption isotherms technique, as an approach to predict the P availability in Colombian coffee soils.

MATERIALS AND METHODS

The study was carried out at the soil laboratory of the National Coffee Research Center (Cenicafé) in Chinchiná, Colombia (Plan Alto headquarters) (5°15'34"N, 75°15'34"W, altitude 1430 m).

Equilibration time

A preliminary test to check equilibration time for the solution of P concentration was conducted in a *Pachic fulvudands* soil. For this purpose, an aliquot of 3 g of soil (dry basis) of the Chinchiná soil (*Pachic fulvudand*) was transferred to a centrifuge plastic tube of 50 mL, that contained 30 mL of 0.01 M of $CaCl_2$ and KH_2PO_4 equivalent to 1000 mg of P per kg of soil. Three drops of toluene were added to each tube to inhibit microbial activity. The tubes were shaken for 30 min twice daily (each 12 h), and this cycle was repeated over 7 days. After the 16th, 36th, 60th, 84th, 108th 132th and 156th hour, the soil solution P concentration was measured by the phosphomolybdate blue method developed by Murphy & Riley (1962). Briefly, a solution

composed of 0.35 g of ammonium potassium tartrate, 168 mL of concentrated sulfuric acid, and 14.43 g of ammonium molybdate was prepared. All these components were diluted in 3.0 L of deionized water. Then, 10 mL of filtered soil solution was added to 2.5 mL of the B-solution (0.428 g of ascorbic L-acid diluted in 100 mL of A-solution). A spectrophotometer was calibrated using standard P solutions of 0.0, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 mg L^{-1}, by adding 2.5 mL of B-solution. After 20 minutes, when the blue color was formed, the absorbance at 890 nm of wavelength was measured.

Soils

Five Andisols and four Inceptisols were selected, which represent the most abundant soil types in the coffee growing regions of Colombia (Table 1). To obtain the soil samples, coffee plantations established for more than 10 years were chosen in different locations. Ten sub-samples of soil were taken randomly in the top 20 cm of the A horizon (peak absorbing root density zone for the coffee) totaling about 2.0 kg soil per location. The soil samples were carried to the Cenicafé soil laboratory, air-dried, and sieved between 0.5 and 2.0 mm apertures-sieves. Approximately 50 g were used for PF analysis, and another fraction was used to evaluate physical and chemical characteristics (Table 2).

Phosphate sorption isotherms

P-sorption isotherms
According to the method developed by Fox & Kamprath (1970), 3 g (dry basis) of soil were transferred by triplicating into 50 mL plastic centrifuge tubes, which contained increasing amounts of P (0, 60, 125, 250, 500, 1000, and 2000 mg kg^{-1}) using KH_2PO_4 diluted in 30 mL de 0.01 M $CaCl_2$. The tubes were shaken in a reciprocal shaker during 30 min, twice daily (each 12 h) for 7 days. Next, the tubes

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Table 1. Selected soils used in this study from different areas traditionally cultivated with coffee plantations for over 10 years.

Soil	Parental material	Order	Taxonomy	Location (Town, Municipality, Department)
Chinchiná	Volcanic ashes	Andisol	Fulvudand	La Quiebra, Chinchiná, Caldas
Timbío	Volcanic ashes	Andisol	Melanudand	San Joaquín, Timbío, Cauca
Líbano	Volcanic ashes	Andisol	Melanudand	La Trinidad, Líbano, Tolima
Doña Juana	Volcanic ashes	Andisol	Hapludand	Bellavista, La Unión, Nariño
Quindío	Volcanic ashes	Andisol	Udivitrand	Río Verde, Buenavista, Quindío
Doscientos	Igneous rock	Inceptisol	Eutropept	Jamundí, Valle del Cauca
San Simón	Igneous rock	Inceptisol	Dystrudept	El Colegio, Ibagué, Tolima
Ropero	Sedimentary rock	Inceptisol	Dystropept	La Honda, El Socorro, Santander
Llano de Palmas	Sedimentary rock	Inceptisol	Dystropept	Árbol solo, El Socorro, Santander

Table 2. Selected properties of the soils studied (depth: 0-20 cm).

Soil property	Chinchiná	Timbío	Líbano	Doña Juana	Quindío	Doscientos	San Simón	Ropero	Llano Palmas
pH (water)	4.6	5.2	5.2	5.2	5.2	5.0	5.2	4.9	4.5
pH (0,1 M KCl)	4.0	4.4	3.0	4.9	4.5	4.4	3.6	3.4	3.5
Δ pH	-0.6	-0,8	-2.2	-0.3	-0.7	-0.7	-1.7	-1.5	-1.0
Organic matter-OM (%)	12.3	17.6	13.4	7.7	6.2	14.4	5.0	6.3	5.7
Bray-P (mg kg^{-1})	2.4	3.7	3.0	34	5,0	13	8.9	4.2	7.0
Exchangeable acidity (cmol$_c$ kg^{-1})	1.9	0.5	0.7	0.4	0.4	0.4	0.2	2.0	1.5
Effective CEC (cmol$_c$ kg^{-1})	2.3	7.6	2.6	5.0	3.7	4.1	12.9	7.1	4.8
Exchangeable Al (cmol$_c$ kg^{-1})	0.8	0.5	0.6	0.2	0.6	0.4	0.2	1.7	1.4
Clay (%)	20	22	11	16	14	26	28	45	39
Sand (%)	54	46	46	67	67	62	50	28	40
Silt (%)	26	32	43	17	19	12	23	27	21

Methods: pH in water (1:1, W:V) and pH in 1 M KCl, potentiometer; Organic matter (OM) content: Walkey and Black; P: Bray II; Effective CEC: Sum of exchangeable cations (Ca+Mg+K+Na+Al); exchangeable acidity: 1 M KCl; clay, silt, and sand contents: Bouyoucos method; ΔpH= pH in KCl- pH in water.

were centrifuged at 6.000 rpm for 10 min to obtain a clean supernatant with P in solution.

Soil solution P concentration

After 6.5 d of equilibration (156 h), the supernatant was filtered through a Whatman filter paper No. 42. Ten mL of the filtrate were used to determine the soil solution P concentration (Murphy & Riley, 1962) as explained above.

Statistical analysis

Data were analyzed based on mean and the standard error. Time equilibration of P in soil solution was evaluated through Duncan test (5%). For all soils evaluated, a regression model to describe the relationship between P applied and P in solution was fitted to estimate the required amounts to achieve a soil solution P concentration of 0.2 mg L^{-1} (P$_{0.2}$ value). All the analyses and statistical tests described in this study were performed using the statistical package SAS version 9.4 © (2016 by SAS Institute Inc. Cary NC, USA). Furthermore,

a classification tree was developed using the variables OM effective CEC, ΔpH, Al, clay, and sand, following the criteria established by Frank et al. (2016). The purpose of this classification tree was to distinguish between soils with low PF capability (≤ 500 mg kg^{-1}) and soils with high PF capability (>500 mg kg^{-1}).

RESULTS

Equilibration time

Changes in the soil solution P concentration over time were observed (Figure 1). At 16 h after the addition of P as KH$_2$PO$_4$, the P level was 0.82 mg L^{-1}. This value had a standard error equivalent to 0.085 mg L^{-1}, which indicated high variability in the equilibration time. After that, the P concentration and its variability were decreasing over time and values of P in the soil solution were between 0.22 and 0.18 mg L^{-1} at 84 and 156 h, respectively, which indicates the most reliable levels of PF and/ or soil solution P, given the small standard error (0.005 mg L^{-1} in average).
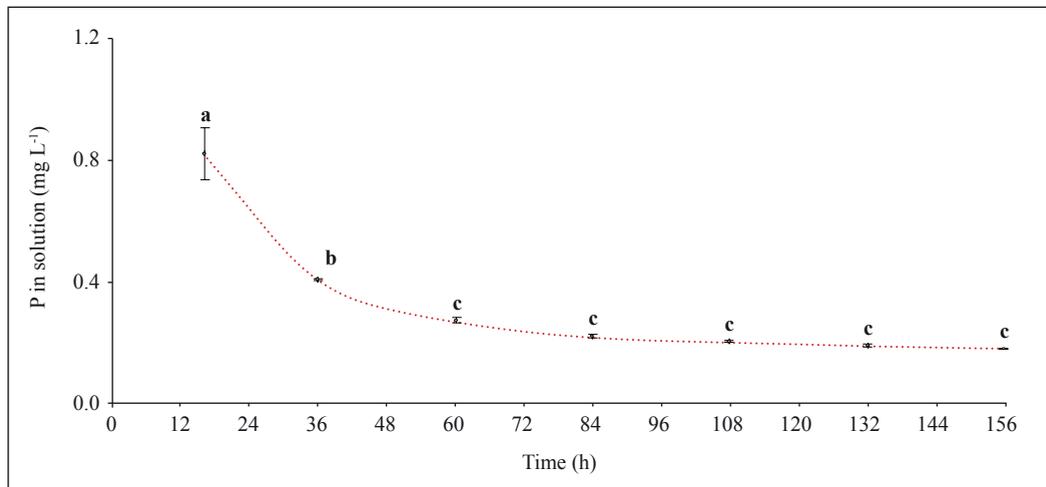
Figure 1. Soil solution P concentration as a function of time of a P adsorption isotherm conducted in the Chinchiná soil. Each value represents the mean of three data; bars indicate standard error. Means with different lowercase letters are significantly different (P<0.05) according to the multiple range test of Duncan.

The obtained data could be represented by statistical model described as following:

$$Ps\,(mgL^{-1}) = \frac{1}{(0.4754 + 0.0479\ t)}$$

Where,

Ps: Soil solution P concentration
t: equilibration time (h).
With r^2= 0.99; Mean square error= 0.0017; P <0.001.

P-Sorption isotherms

To understand the relationship between PF and $P_{0.2}$, the fitted value of $P_{0.2}$ (y-axis) against P application rate (x-axis) was determined, as shown in figures 2 and 3, for Andisols and Inceptisols, respectively. The magnitude of PF was different among several soils (Table 3). Among Andisols group, the Chinchiná soils had the highest PF, and its $P_{0.2}$ value was achieved with P applications of 773 mg kg^{-1}. Soils from Timbio, Líbano, Quindio and Doña Juana needed P applications of 615, 531, 356 and 104 mg kg^{-1}, respectively. Concerning Inceptisols, the $P_{0.2}$ level in the soil solution was achieved with 349 mg kg^{-1} in the Doscientos soil, with 257 mg kg^{-1} on average in the Ropero and Llano Palmas soils. No P addition was needed in San Simon to reach a $P_{0.2}$ value.

The statistical model fitted for each soil, corresponded to an exponential expression: **y= α (β)^x**, where:

y: P-solution; α and β: Function parameters, **x:** Amounts of P applied.

Calculations of PF in all the soils studied can be obtained from function parameters given in table 4.

Table 3. Soil classification according to P application requirement to achieve $P_{0.2}$ and relative PF to reach $P_{0.2}$ levels in the different soils relative to Chinchiná soil (100%).

Soil	$P_{0.2}$ (mg kg^{-1})*	Relative value (%)
Chinchiná	773.2	100
Líbano	531.2	80
Timbío	615.0	69
Quindío	356.4	46
Doña Juana	104.1	45
Doscientos	349.8	35
Ropero	270.9	31
Llano Palmas	242.5	13
San Simón	0.0	0

*P application rate (mg kg^{-1} soil) required to obtain a concentration equivalent to 0.2 mg L^{-1}.

Classification tree

The analysis with the variables, OM, effective CEC, ΔpH, Al, clay and sand content, showed that, from the OM level it is possible to classify the PF soils. According to the findings, there is a 66.67% probability that a soil with an OM content of at least 7.7% can be classified as having a low PF level (Figure 4).

DISCUSSION

Equilibration time

The initial readings of soil solution P were quite variable (12 h), but this variability is reduced over time, remained constant (equilibrated) after 60 hours, once adsorption and desorption

Table 4. Regression parameters for soils studied $f(x) = \alpha (\beta)^x$.

| Soil	Parameter	Estimate	SE	CL		Pr > F	R²
Chinchiná	Alpha	0.062	0.00657	0.048	0.076	<0.0001	0.97
	Beta	1.039	0.00142	1.036	1.042		
Líbano	Alpha	0.048	0.00779	0.032	0.065	<0.0001	0.99
	Beta	1.142	0.01020	1.121	1.164		
Timbío	Alpha	0.019	0.00517	0.008	0.030	<0.0001	0.98
	Beta	1.154	0.01840	1.114	1.194		
Quindío	Alpha	0.028	0.00450	0.018	0.037	<0.0001	0.96
	Beta	1.092	0.00623	1.079	1.105		
Doña Juana	Alpha	0.004	0.00096	0.002	0.006	<0.0001	0.99
	Beta	1.176	0.00914	1.156	1.196		
Doscientos	Alpha	0.122	0.01940	0.081	0.163	<0.0001	0.94
	Beta	1.046	0.00262	1.041	1.052		
Ropero	Alpha	0.031	0.01290	0.003	0.059	<0.0001	0.97
	Beta	1.075	0.01470	1.043	1.106		
Llano Palmas	Alpha	0.020	0.00360	0.012	0.027	<0.0001	0.99
	Beta	1.096	0.00611	1.083	1.109		
San Simón	Alpha	0.126	0.01730	0.089	0.163	<0.0001	0.98
	Beta	1.157	0.00678	1.143	1.172		

SE: Standard error. CL: Confidence Limits (95%).
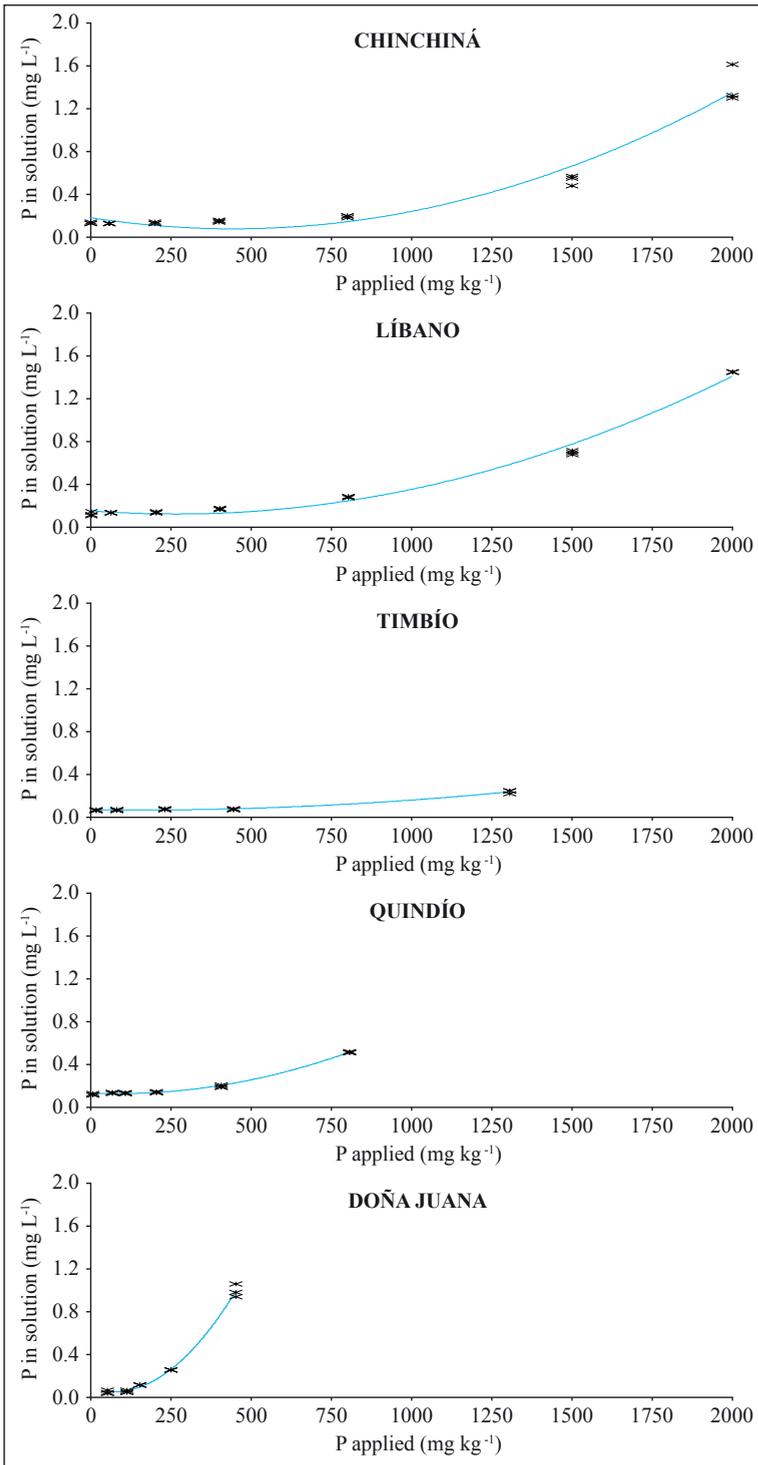
Figure 2. Relationship between the amounts of P applied and the soil solution P concentration in the Andisols.
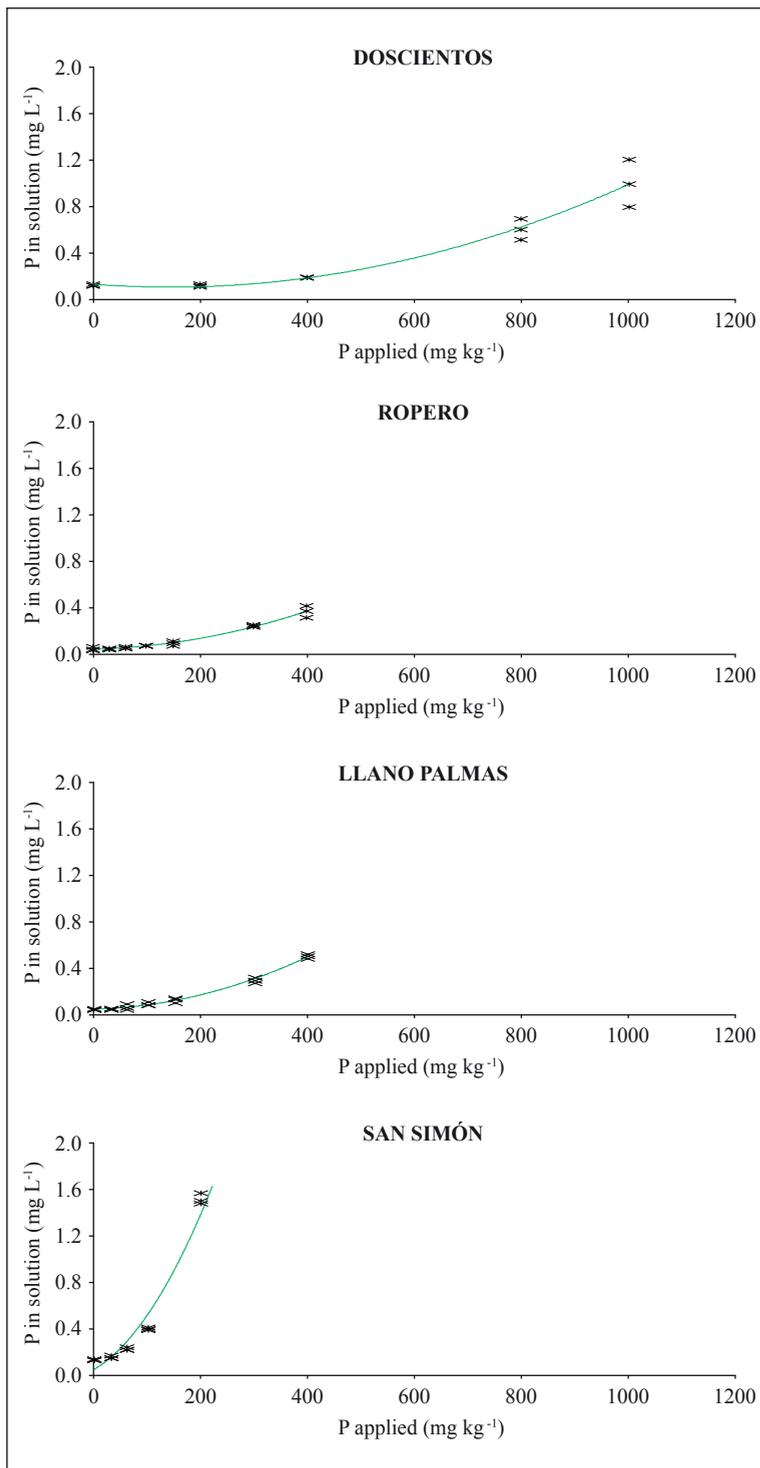
Figure 3. Relationship between the amounts of P applied and the soil solution P concentration in the Inceptisols.
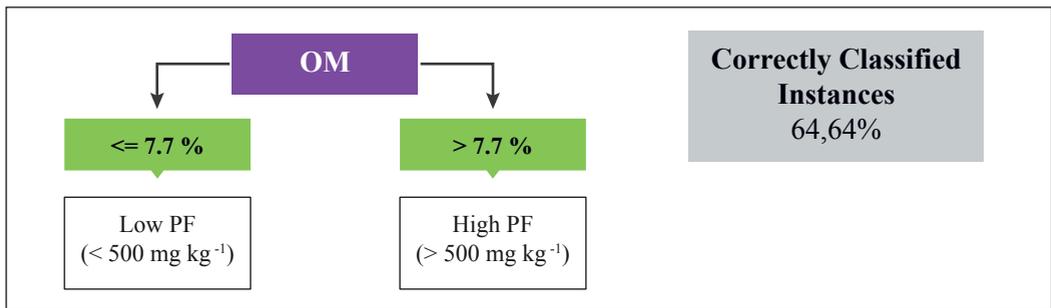
Figure 4. Classification tree, explaining PF from SOM content in all the soils studied.

reactions equilibrium was reached. Therefore, a duration between 60 h and 156 h was proposed to obtain most reliable results, contrary to the USDA recommendation for Andisols (classified by high PF capability) of 24 h (USDA, 2014). Our results are according with those by Fox & Kamprath (1970) who found that the equilibration time was reached after 6 days in a P adsorption isotherm conducted in an Ultisol (recognized by high PF).

Several authors had used less equilibration times (< 48 h) in P adsorption isotherms, such as in models of Langmuir or Freundlich to explain the dynamic and magnitude of the process to soils beyond the scope of this investigation (Poveda & Sadeghian, 2023, Alovisi et al. 2020; Díaz & Sadeghian, 2018, Cao et al. 2017, Shafquat & Pierzynski 2014, and Gauthan & Prabhaker, 2012), and miscellaneous materials which have a weak PF capability such as labile organic matter derived from harvest residues and activated biochar (Ziwei et al., 2026, Chanda et al. 2025), or materials with a slower adsorption rate constant like eggshell (Sarkar et al. 2025). Our study did not consider these models, because the retention force depends on the amount of P adsorbed, the adsorption is not a monolayer phenomenon, P adsorption sites were unevenly distributed on the colloid surface, and precipitation of phosphate with Al and Ca ions occurred in parallel (Gupta et

al. 2020, Sparks, 1995). This seems evident only under specific levels of P evaluated in the isotherms, for instance, as found by Dunne et al (2021) who worked with Langmuir and Freundlich parameters, predicted satisfactory PF employed P concentrations less than 50 mg L^{-1}. In our research amounts between 0–2 000 mg L^{-1} of P were evaluated.

P-Sorption isotherms

PF in Andisols results from processes including non-crystalline materials such as allophane, imogolite, Al-humus complexes, ferrihydrite and the active surfaces at silicate minerals (Shoji y Takahashi, 2002). Results reported by Gonzalez & Sadeghian (2012), in the same soil profiles corresponding to Chinchiná and Quindío soils, indicated in both cases, mineral traces of volcanic ash (<5%), andesite, hypersthene and zircon, and high content of (6-15%) magnetite, quartz and other weathered minerals. It is worth mentioning that non-crystalline material present at Chinchiná soil was above 50%, while in Quindío the contents were between 30 and 50%. The differences mentioned explain variations in the PF among Andisols.

In relation with soil fertility status, variables like, OM, ∆pH and sand content provide valuable information to explain PF in the Andisols studied. In the first place, ∆pH is

widely accepted as an indicator of net charge on the colloids surface (Kome et al. 2018), indicating the prevalent magnitude of negative charges, avoiding the P sorption. Furthermore, in the same soil type, while OM content in Chinchiná, Líbano and Timbío was above 12% and the sand percentage was lower than others (average 49 %), in Quindío and Doña Juana, the OM were 6.2 and 7.7 % respectively and the sand content was around 67%.

Regarding OM, the tendency can be associated to the specific surface in allophane, which corresponds to 257-374 m^2 g (Huang et al. 2016), combined to positive charges of OM, which can generate organic-mineral complex, against biodegradation (Mabagala & Mng'ong'o, 2022). As an outcome, OM prevents or inhibits crystallization of Al and Fe, which form stable complexes with them, and maintain ores with less ordinated range (non-crystalline and amorphous minerals), which in turn, generate a greater specific surface area to fixing P (Campos et al. 2016; Pizzeghello et al. 2014; Peña-Ramírez et al. 2009). Chemical forms of Fe and Al (OM-Fe^{3+}, OM-$Fe(OH)^{2+}$, OM-Al^{3+}, OM-$Al(OH)^{2+}$) associated with OM, also control, to a large extent, the high PF. Under these considerations, an increase of PF occurred where the exchange acidity and the Al content were highest (Table 2). In Portugal Jalali & Jalali (2016), reported PF from 99 to 4406 mg kg^{-1} and found a strong relationship among those chemical properties and SOM levels.

Similar requirements of $P_{0.2}$ in Doscientos soil are associated to its high OM content (>14%). This behavior can be explained considering that the Doscientos soil appears in the intermediate strip into hill, where Andisols and Doscientos are connected to each other. Under these conditions, some volcanic ashes deposits, and particles such as amorphous clay minerals are commonly found in the soil profile of the Doscientos soil (González, 2013). However, this condition is not sufficient to classify Doscientos into the Andisol order.

To Llano Palmas and Ropero soils, where OM was the lowest (5.7 y 6.3%, respectively), a major PF was expected due to its highest clays contents (among 39 and 45%), which generating a considerable specific area. Although Shafqad & Pierzynski (2014) reported under high clay content soils that PF can occur but with low magnitude. Additionally, the Al^{3+} actively participated in the PF (Chen & Liao, 2016), under this consideration a significant content of this metallic ion explains PF in both soils. In the San Simon soil, the association that has been discussed did not occur. Nevertheless, since this soil was derived from a granodiorite rock, whose sands are coarse (bigger than 0.5 mm), it showed low specific area surface, San Simon had the lowest P-requirements to achieve $P_{0.2}$ level among the soils studied. Similar results achieved by Spohn et al. (2020) in Chilean soils derived from granodiorite, demonstrated that highest sand content derived a lower surface area of mineral particles, thus a low capability of P sorption. Arai & Livi (2013) demonstrated that the sand fraction in soils exhibits chemical reactivity to P sorption only under specific chemical configuration based on alumina- silicates and iron.

Taking in consideration the results of P isotherms in Colombian coffee soils, P amounts of coffee fertilizations can be modified to the extent of precisions according to the objective, for instance, a recommendation to a specific coffee cultivar, crop stage or biotechnological strategy. In relation to the technological option, $P_{0.2}$ is accepted as an optimal indicator. Jaramillo & Osorio (2009), Habte & Bittenbender (1999) and González-Osorio et al. (2022) established recommendations based on $P_{0.2}$ or around, to promote growing coffee seedlings throughout

mycorrhizal association. Yost et al. (1981), who worked with P-Sorption isotherms, suggested indicators to predict that the efficient use in P fertilizations could be possible and correlated these results with any methodology to estimate P disposable by roots. In Brazilian soils, Roy et al. (2017) obtained a significant correlation between PF and the nutrient extracted by P in the Bray II methodology, which indicated that knowing PF values constitutes a great alternative to predicting and calculating P requirements by crops.

CONTRIBUCIÓN DE LOS AUTORES

Conceptualización, Curación de datos, Investigación y Metodología: **HGO**; Análisis formal: **HGO-RDMR-WO**; Redacción: **HGO-CEGB** original: **HGO-CEGB**; Redacción–revisión y edición: **HGO-CEGB-WO**. Todos los autores han leído y aceptado la versión publicada del manuscrito

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