

# Identification of acid-tolerant coffee genotypes in a coffee germplasm collection of Colombia

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## ABSTRACT

One of the limitations of coffee production in many regions of Colombia is the soil acidity. According to historical soil chemical analysis records, more than 50% of coffee farms have pH values below 5.0. Because acid-tolerant coffee varieties are not available, farmers use calcareous additives to correct the problem, which incurs associated labor and input costs. The objective of this work was to identify acid-tolerant genotypes of *Coffea arabica*. For two contrasting soils in the coffee-growing area of Colombia (Andisol and Entisol), the effect of soil acidity on the growth of 20 genotypes of *Coffea arabica* during the seedling stage was evaluated. The genotypes were wild accessions that make up the Colombian Coffee Germplasm Collection and the Castillo<sup>®</sup> Naranjal Variety, used as commercial material. Six months after the seedlings were transplanted into soils treated with or without acidity correction additives, the weight of the dry matter of the roots, stems and leaves was recorded. Later, the acid-tolerant genotypes were identified by means of the quadrant method and the tolerance index. The Timor Hybrid and Rume Sudan genotypes were identified as tolerant of the acidity of the two soil types. These genotypes could be used as progenitors in a coffee breeding program leading to a commercial coffee variety tolerant to soil acidity.

**Key words:** Andisol; entisol; *Coffea arabica* L.; timor hybrid; rume sudan.

## 1 INTRODUCTION

Soil acidity limits global crop production to approximately 30% of the Earth's surface, which corresponds to 50% of the world's potentially cultivable land. The tropical and subtropical zones represent 60% of the world's acidic soils. In tropical regions, approximately 43% of soils are acidic, with 68% of these soils found in tropical America (Yang; Rao; Horst, 2013). In addition to containing toxic levels of aluminum ( $Al^{3+}$ ) and manganese ( $Mn^{2+}$ ), acidic soils are deficient in nutrients, especially calcium ( $Ca^{2+}$ ), magnesium ( $Mg^{2+}$ ) and phosphorus (P), which affect crop development and productivity (Havlin et al., 2014; Rao, 2014; Rao et al., 2016).

According to soil analysis records from the Colombian coffee grower zone performed over the last 20 years, a high percentage of the tested samples had pH values lower than 5.0 and  $Al^{3+}$  levels greater than  $1.0\text{ cmol}_c\text{ kg}^{-1}$  (Sadeghian, 2013). Fifty-two percent of coffee-growing areas corresponded to volcanic ash-derived, P-fixing, high organic matter content soils with iron and aluminum oxides, hydroxides and pH values lower than 5.5, all of which are factors that negatively affect nutrient availability for coffee plants (Valencia, 1999). At the rainiest sites in the Colombian coffee-growing region, great losses occur through the leaching of alkali or basic cations such as Ca, Mg and K, which are replaced by acidic cations, mainly H, Al, Fe and Mn. Organic matter decomposition, sulfur oxidation and ammonium nitrification are also naturally occurring processes that contribute to the increased soil acidity in these regions (Zapata, 2004). Similar

effects have been observed in *C. arabica* plantations in Indonesia (Hanisch et al., 2012). For the growth of coffee in Colombia, specifically in relation to the seedling stage, soils with pH values between 4.9 and 5.7 and  $Al^{3+}$  contents of less than  $1.10\text{ cmol}_c\text{ kg}^{-1}$  are considered adequate (Sadeghian; Díaz, 2020).

The use of lime, phosphorus fertilizers and organic inputs is recommended to correct the soil acidity and provide deficient nutrients, and this is practiced in many agricultural systems in temperate and tropical climates. Although liming can raise the soil pH and remediate low surface acidity, the subsoil is typically not affected because the deep incorporation of lime is technically difficult and expensive, making it a controversial alternative, in addition to the fact that the continued use of agrochemicals has side effects that cast doubt on their environmental sustainability (Rao, 1993; Rao, 2014; Rheinheimer et al., 2000).

An integrated soil management program that includes site-specific additives and the use of microorganisms and commercial products to correct soil acidity is a strategy to address soil acidification, although these practices would result in additional costs for farmers. In view of the above, the genetic mechanisms that plants have developed to tolerate acidity could be exploited and genotypes that can be used for the production of new acid-tolerant varieties could be identified. The incorporation of these varieties into an integrated soil management program would increase efficiency, mitigate environmental impacts and reduce production costs for farmers.

The Colombia National Coffee Research Center (CENICAFÉ) has a coffee germplasm collection composed of more than 1,000 accessions, which includes different species, hybrids, varieties and elite genotypes of *Coffea* sp. However, no studies focused on identifying genotypes tolerant to the acidic soil conditions have been conducted with this collection. Therefore, the present study evaluated 20 genotypes representative of the genetic variability of the collection, which were grown in two soil types with low acidity, and genotypes that showed tolerance to this physiological stress were identified.

## 2 MATERIAL AND METHODS

### 2.1 Plant material

A total of 19 genotypes were randomly selected from the list of 54 genotyped accessions that make up the core of the coffee germplasm collection and are grouped using the nearest neighbor method according to pairwise genetic distance (Moncada and Maldonado, personal communication). These genotypes are part of the Germplasm Bank of CENICAFE and are wild accessions of *C. arabica* that were collected in several African expeditions in the 1960s. The Castillo® Naranjal variety, which is resistant to coffee rust and has been grown since 2005 in the central Colombian coffee-growing region, was used as a commercial genotype (Alvarado et al., 2006).

### 2.2 Soil

In a coffee farm in the municipality of Cubarral (Meta, Colombia) and in the Naranjal Experimental Station (municipality of Chinchiná, Caldas, Colombia), 2.0 t of soil at a depth of 0.20 m were collected. These soils, classified as Entisol and Andisol, respectively, were characterized as being acidic for coffee cultivation and had contrasting properties. The amount of dolomitic limestone required to correct the acidity in each case was determined according to the pH value. Subsequently, half of the soils were limed, watered and incubated for one month, after which time their physicochemical characteristics were determined (Table 1) according to the methods described by Carrillo (1985).

### 2.3 Sowing of genotypes

Seeds were collected from the 19 genotypes of the Colombian Coffee Germplasm Collection and from the Castillo® Naranjal variety used as commercial material. Germinators were set up and when seedlings were obtained, they were planted in 0.17 m x 0.23 m black plastic bags, according to the soil type and acidity condition. Subsequently, the plants were placed in a flat area covered with shade cloth that allowed transmission of 43% of the photosynthetically active radiation. Agronomic plant management was performed

according to the technical recommendations of CENICAFE, applying 0.002 kg plant<sup>-1</sup> of diammonium phosphate (DAP) fertilizer at two and four months (Sadeghian, 2008; Gaitán et al., 2013). At six months, the plants were collected, soil residues were removed, and the plant height and root length of each plant were measured. The plants were individually packed in paper bags, labeled according to the treatment and dried in an oven at 75 °C for 72 h. The weight of the dry biomass of each plant was measured using an analytical balance (1 x 10<sup>-6</sup> kg).

**Table 1:** Physicochemical characteristics of the Entisol and Andisol used for the evaluation of acid-tolerant *C. arabica* genotypes.

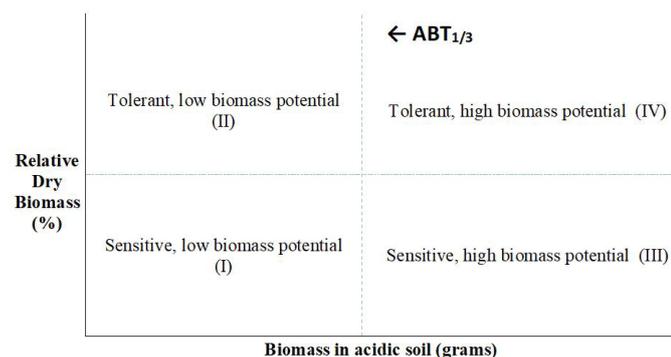
	Andisol (Naranjal)		Entisol (Cubarral)	
	Acidic	Amended	Acidic	Amended
pH	4.50	5.20	3.90	5.20
K (cmol <sub>c</sub> kg <sup>-1</sup> )	0.40	3.87	1.80	3.68
Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	1.62	3.94	0.58	5.53
Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	0.36	1.32	0.19	2.06
Na (cmol <sub>c</sub> kg <sup>-1</sup> )	0.02	0.14	0.02	0.13
Al (cmol <sub>c</sub> kg <sup>-1</sup> )	0.90	0.20	1.00	0.20
P (kg kg <sup>-1</sup> )	6x10 <sup>-6</sup>	9x10 <sup>-6</sup>	1.29 x 10 <sup>-4</sup>	9.9 x 10 <sup>-4</sup>
Organic matter (%)	7.0		5.0	
Texture	Loamy, sandy		Loamy, sandy, clayey	

### 2.4 Experimental design

A total of 25 experimental units were planted per treatment, and the number of replicates was statistically defined according to the following criteria determined in previous CENICAFE experiments: estimated variance of 4.687 associated with the total dry matter weight in six-month-old seedlings; minimum significant difference of 0.0015 kg; level of significance of 5% and reliability of 89%. The response variable was the dry matter weight, and plant height and root length recorded at six months of cultivation were the complementary variables. The effect of the treatments was evaluated by two methods used by the International Center for Tropical Agriculture-CIAT for the development of varieties tolerant to acidic soil (Howeler, 1990; Nicholaides; Piha, 1990).

**Quadrant method:** A Cartesian coordinate was constructed (Figure 1) in which the dry matter under acidic soil conditions is represented by the X-axis and the relative biomass (%) by the Y-axis. The latter corresponds to the relationship between the dry biomass in the unlimed soil and the dry biomass in the amended soil, expressed as a percentage. Then, the area of the figure delimited by these axes was divided horizontally into two by a line drawn at the 80% relative biomass level (Y-axis) to separate the acid-tolerant genotypes (above the line) from the acid-sensitive

genotypes (below the line). The literature suggests using 80% relative biomass to assess the tolerance to acidic soil, but if the researcher requires a stricter criterion, this line can be drawn at the 85% level. Lastly, a line was drawn vertically through the X-axis at the level of the mean dry matter weight of the best one-third of the genotypes sown in the amended soil, forming four areas or quadrants in the figure. The genotypes that were distributed in quadrant IV were selected as tolerant to acidic soil (Nicholaides; Piha, 1990).



**Figure 1:** Model of the quadrant method used to differentiate genotypes according to their tolerance to soil acidity and their biomass potential under these stress conditions. Relative dry biomass = (dry biomass weight without liming/dry biomass weight with lime);  $ABT_{1/3}$  is the average biomass of the top one-third of the genotypes in soil treated with lime (Nicholaides; Piha, 1990).

**Tolerance index method:** This index was calculated using equation (1). Genotypes with a tolerance index greater than or equal to 1.0 were selected as tolerant to acidic soil (Howeler, 1990).

$$\text{Tolerance index} = \frac{\text{Dry biomass without lime}}{\text{Dry biomass with lime}} * \frac{\text{Mean dry biomass without lime}}{\text{Maximum dry biomass without lime}} \quad (1)$$

#### Selection of tolerant *C. arabica* genotypes:

Genotypes that were distributed in quadrant IV and had a tolerance index greater than 1 were selected as progenitors for a breeding strategy for acidic soil tolerance. With the complementary variables, plant height and root length, a *t*-test (95%) was performed comparing each population with respect to the overall mean of their corresponding acidity condition.

## 3 RESULTS AND DISCUSSION

### 3.1 Soil properties

The soil properties analyzed before and after liming are shown in Table 1. In the two soil samples, the initial

exchangeable aluminum content ( $Al^{3+}$ ) was practically the same ( $1 \text{ cmol}_c \text{ kg}^{-1}$ ), while the pH of the Entisol was lower (3.8) than that of the Andisol (4.5). The Entisol had a significantly higher phosphorus content ( $1.29 \times 10^{-4} \text{ kg kg}^{-1}$ ) compared to the Andisol ( $6 \times 10^{-6} \text{ kg kg}^{-1}$ ), and it is known that inert phosphorus, aluminum, iron and non-apatite calcium phosphates predominate in Entisols. As expected, the organic matter content was higher in the Andisol. In terms of physical differences, the Entisol exhibited a sandy-loamy-clayey texture and a brownish yellow color, while the Andisol was sandy-loamy and black.

Liming was used to correct soil acidity (by increasing pH and neutralizing  $Al^{3+}$ ) to the adequate range for coffee cultivation (Sadeghian, 2013) and to increase the  $Ca^{2+}$ ,  $Mg^{2+}$  and  $K^+$  levels (Table 1). The results showed the benefits of applying dolomite to acidic soils and confirmed reports in previous studies on coffee cultivation (Valencia; Bravo, 1981; Correa et al., 2007; Vilela et al., 2010).

### 3.2 Plant Biomass

Table 2 shows the mean dry biomass values of the genotypes grown in Entisol and Andisol under the two soil acidity levels. A positive response was observed in approximately 35% of the genotypes planted in Entisol soil when lime was applied. Table 2 also shows the mean dry matter values of the genotypes grown in Andisol. In this case, the biomass increased with acidity correction in 35% of the genotypes.

### 3.3 Selection of acid-tolerant genotypes

#### 3.3.1 Quadrant method

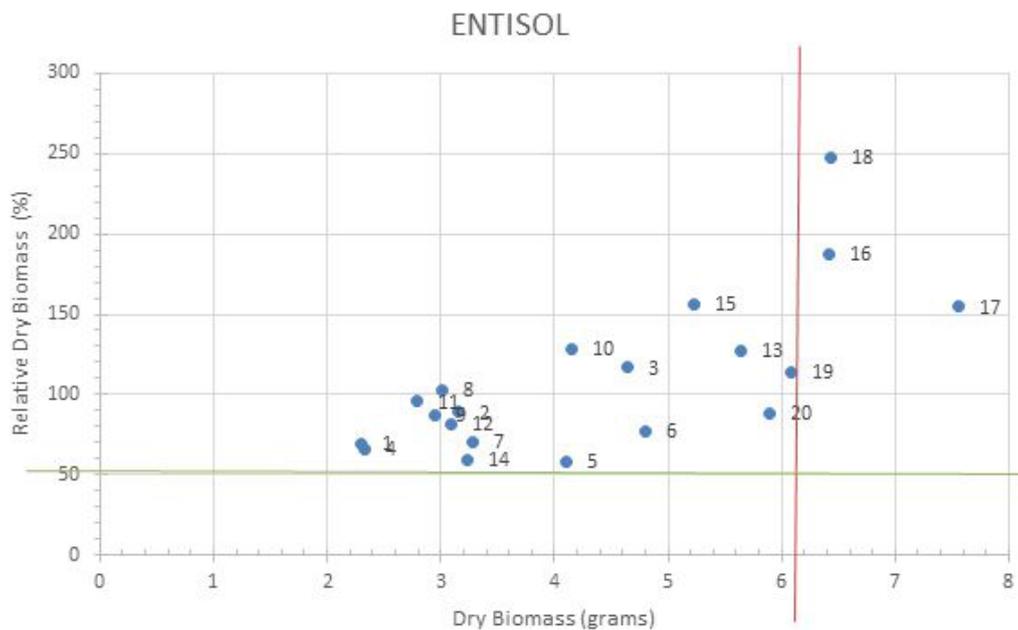
In both soil types, there was variability in the tolerance to acidity of the cultivated genotypes, a result that is evidenced by the dispersal of the wild coffee accessions throughout quadrants I, II and IV (Figures 2 and 3). The Timor Hybrid, S-17 Irgalem and Rume Sudan genotypes were distributed in quadrant IV, indicating tolerance to acidity in Entisol (Figure 2). For Andisol, the E146, Castillo Naranjal, S-17 Irgalem, Timor Hybrid and Rume Sudan genotypes were distributed in quadrant IV (Figure 3).

#### 3.3.2 Tolerance Index Method:

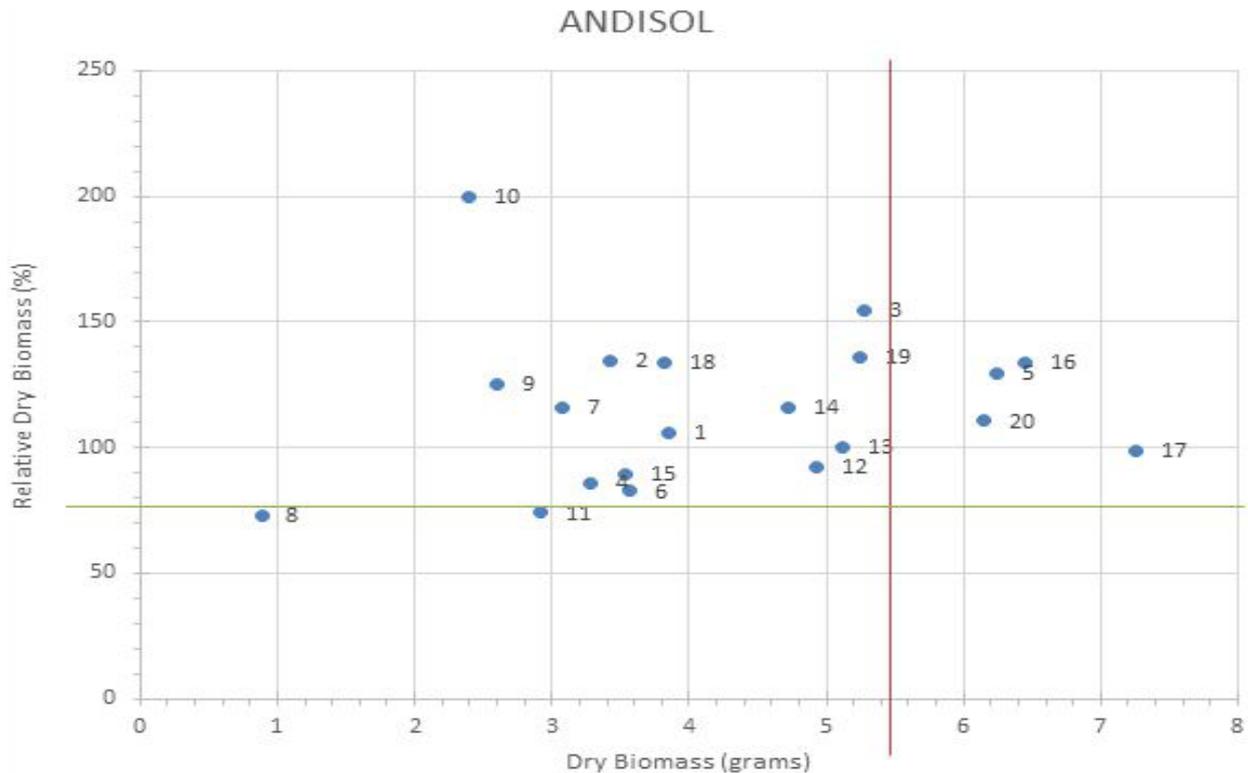
Table 3 describes the results obtained for the tolerance indices of the genotypes grown in the two soil types under acidic conditions. In Entisol, the S-17 Irgalem, Timor Hybrid and Rume Sudan genotypes had an index greater than 1.0, while in Andisol, the E146, E085 and Timor Hybrid genotypes had a tolerance index greater than 1.0; however, the Rume Sudan genotype obtained a value of 0.98.

**Table 2:** Mean dry matter of genotypes grown in Entisol with pH 3.9 and corrected with lime to pH 5.2 in Andisol with pH 4.5 and corrected with lime to pH 5.2; SE = standard error.

GENOTYPE	ENTISOL				ANDISOL			
	Dry matter (kg plant <sup>-1</sup> )				Dry matter (kg plant <sup>-1</sup> )			
	ACIDIC	SE	AMENDED	SE	ACIDIC	SE	MENDED	SE
E364	0.00302	0.00042	0.00294	0.00038	0.00088	0.00022	0.00121	0.00046
E365	0.00295	0.00046	0.0034	0.00051	0.00378	0.00062	0.00208	0.00037
E336	0.00328	0.0005	0.00467	0.00041	0.00308	0.00043	0.00266	0.00054
E146	0.00411	0.00039	0.00709	0.00052	0.00625	0.00041	0.00481	0.0005
E290	0.00481	0.00064	0.00621	0.00058	0.00357	0.00036	0.00432	0.00044
E085	0.00465	0.00051	0.00398	0.00056	0.00528	0.00064	0.00341	0.00064
E071	0.00315	0.0003	0.00354	0.00045	0.00343	0.00026	0.00254	0.00041
E042	0.0023	0.00026	0.0033	0.00035	0.00385	0.0005	0.00363	0.00059
E428	0.00279	0.00023	0.00293	0.0004	0.00292	0.00022	0.00395	0.00035
E114	0.00233	0.00019	0.00353	0.00038	0.00329	0.00022	0.00383	0.00037
E420	0.00415	0.00029	0.00323	0.00037	0.00239	0.00027	0.0012	0.00034
E554	0.00309	0.00021	0.0038	0.00043	0.00493	0.00027	0.00535	0.0004
ET57	0.00523	0.00049	0.00334	0.00055	0.00354	0.00028	0.00396	0.00046
ET06	0.00563	0.00039	0.00442	0.00042	0.00512	0.00046	0.0051	0.00044
ET27	0.00324	0.00023	0.00546	0.00036	0.00472	0.00027	0.00406	0.0006
SL-28	0.00609	0.00059	0.00535	0.00044	0.00525	0.00036	0.00386	0.00043
Castillo Naranjal	0.0059	0.00047	0.00667	0.00058	0.00614	0.00058	0.00555	0.00047
S-17 Irgalem	0.00643	0.00055	0.0026	0.00037	0.00381	0.00053	0.00285	0.00037
Timor Hybrid	0.00642	0.0007	0.00342	0.00043	0.00645	0.00055	0.00481	0.00067
Rume Sudan	0.00756	0.0006	0.00489	0.00059	0.00726	0.00041	0.00735	0.00071



**Figure 2:** Quadrant model for the selection of *C. arabica* genotypes tolerant to acidic Entisol soil. Genotypes 16, 17 and 18 were distributed in the upper right quadrant (IV) and were considered acid tolerant. 1: E042, 2: E071, 3: E085, 4: E114, 5: E146, 6: E290, 7: E336, 8: E364, 9: E365, 10: E420, 11: E428, 12: E554, 13: ET06, 14: ET27, 15: ET57, 16: Timor Hybrid, 17: Rume Sudan, 18: S17-Irgalem, 19: SL-28, 20: Castillo Naranjal.



**Figure 3:** Quadrant model for the selection of *C. Arabica* genotypes tolerant to acidic Andisol soil. Genotypes 5, 16, 17 and 20 were distributed in the upper right quadrant (IV) and were considered acid tolerant. 1: E042, 2: E071, 3: E085, 4: E114, 5: E146, 6: E290, 7: E336, 8: E364, 9: E365, 10: E420, 11: E428, 12: E554, 13: ET06, 14: ET27, 15: ET57, 16: Timor Hybrid, 17: Rume Sudan, 18: S17-Irgalem, 19: SL-28, 20: Castillo Naranjal.

Considering the results obtained through the application of both methods, the Rume Sudan, Timor Hybrid and S-17 Irgalem genotypes were preselected as acid tolerant in Entisol. These three genotypes were distributed in quadrant IV and had tolerance indices  $>1$ . The Rume Sudan genotype had the highest dry biomass (0.00756 kg;  $P(T \leq t) 0.04$ ) and the greatest height (0.438 m;  $P(T \leq t) 0.04$ ), followed by the S-17 Irgalem (0.00643 kg) and Timor Hybrid (0.00642 kg) genotypes. Regarding root lengths, no significant differences were found among these three genotypes (Table 4).

The Rume Sudan, Timor Hybrid, E146 and E085 genotypes were preselected as acid tolerant in Andisol. The four genotypes were distributed in quadrant IV and had tolerance indices  $>1.0$  except for the Rume Sudan genotype, which had an index of 0.98. However, Rume Sudan had the highest dry biomass (0.00726 kg;  $P(T \leq t) 0.000001$ ) and a greater height than all three of the selected genotypes (0.4303 m;  $P(T \leq t) 0.0002$ ), followed by the Timor Hybrid (0.00645 kg;  $P(T \leq t) 0.0003$ ) and E-146 (0.00638 kg  $P(T \leq t) 0.0001$ ) genotypes, with the latter having the greatest height (0.431 m  $P(T \leq t) 0.0007$ ). For this reason, the Rume Sudan genotype was selected, although the tolerance index was below but very close to 1.0. Regarding root lengths, no significant differences were found among these genotypes (Table 5).

Analysis of these results shows that the Rume Sudan and Timor Hybrid genotypes are tolerant to acidity in both soil types, and therefore, they can be selected as promising candidates as progenitors in a coffee breeding program. Timor Hybrid is one of the progenitors of the Castillo variety and its regional lines, including the Castillo Naranjal variety, which was found to be moderately tolerant to the acidity of the Andisol soil, and it was classified within quadrant IV (Figure 3) but had a tolerance index very near to 1.0 (Table 3).

The results of various studies have demonstrated the positive effect of liming on the growth of coffee plants in the nursery stage (Pavan; Bingham; Pratt, 1982; Pavan et al., 1982; Rodrigues et al., 2001; Rodrigues et al., 2006). In this experiment, it was expected that acidity correction and increases in the contents of exchangeable bases would increase the plant biomass of all genotypes in the two soils; however, this did not occur. The lack of response by some of the plant materials may originate from the application of phosphorous, an element that facilitates root growth and, consequently, greater nutrient absorption. In addition, phosphorous can bind to  $Al^{3+}$  and reduce its toxicity by forming insoluble phosphates with this element (Zapata, 2014). According to the conditions of soil acidity established for coffee growing in Colombia ( $5.0 > pH < 5.5$  and  $Al^{3+}$

<1.10 cmol<sub>c</sub> kg<sup>-1</sup>), both soils were acid, being higher in the Entisol. Potassium (K<sup>+</sup>) fertilization was not included, just the amendment with dolomite to raise the pH greater than 5.0, neutralize Al<sup>3+</sup> and increases Ca<sup>2+</sup> and Mg<sup>2+</sup>. One reason to explain the high increment of K<sup>+</sup> would be the correction of acidity (Table 1). In order to improve the relationship between the bases the application of an additional dosis of dolomite would have been feasible but it would have further increased the pH, exceeding the optimal range for coffee (Sadeghian; Díaz, 2020).

Most agricultural species are susceptible to soil acidity. This problem can be overcome by either correcting the acidity by adding liming materials or by selecting genotypes or varieties tolerant to this stress condition. The second alternative is more practical because the application of lime incurs costs and only alters the upper soil layers, causing the formation of shallow root systems in crops sensitive to acidity. The selection of tolerant genotypes allows for good yields with minimal application of lime (Howeler, 1990).

**Table 3:** Tolerance index of coffee genotypes grown in Entisol and Andisol, calculated using equation (1) described in the Materials and Methods section.

GENOTYPE	ENTISOL			ANDISOL		
	Dry matter (kg kg <sup>-1</sup> )		TOLERANCE INDEX	Dry matter (kg kg <sup>-1</sup> )		TOLERANCE INDEX
	Acidic/Amended	Acidic/Max. Acidic		Acidic/Amended	Acidic/Max. Acidic	
E364	1.03	0.40	0.41	0.73	0.12	0.09
E365	0.87	0.39	0.34	1.25	0.36	0.45
E336	0.70	0.43	0.30	1.16	0.42	0.49
E146	0.58	0.54	0.31	1.30	0.86	1.11
E290	0.77	0.63	0.49	0.83	0.49	0.40
E085	1.17	0.61	0.71	1.55	0.72	1.12
E071	0.89	0.41	0.37	1.35	0.47	0.63
E042	0.70	0.30	0.21	1.06	0.53	0.56
E428	0.95	0.37	0.35	0.74	0.40	0.30
E114	0.66	0.31	0.20	0.86	0.45	0.39
E420	1.29	0.55	0.70	2.00	0.33	0.65
E554	0.81	0.41	0.33	0.92	0.68	0.62
ET57	1.57	0.69	1.08	0.90	0.49	0.43
ET06	1.27	0.74	0.94	1.00	0.70	0.70
ET27	0.59	0.43	0.25	1.16	0.65	0.75
SL-28	1.14	0.80	0.91	1.36	0.72	0.98
Castillo Naranjal	0.88	0.78	0.69	1.11	0.84	0.93
S-17 Irgalem	2.47	0.85	2.09	1.34	0.52	0.70
Timor Hybrid	1.88	0.84	1.59	1.34	0.88	1.18
Rume Sudan	1.55	1.00	1.54	0.99	0.99	0.98

**Table 4:** *C. arabica* genotypes selected as tolerant to soil acidity in Entisol after analysis of the treatment effect using the quadrant method and the tolerance index.

GENOTYPE	QUADRANT METHOD	ENTISOL			TOLERANCE INDEX
		Dry weight (kg)	Root length (m)	Height (m)	
S-17 Irgalem	4	0.00643	0.3118	0.3997	2.09
Timor Hybrid	4	0.00642	0.283	0.4036*	1.59
Rume Sudan	4	0.00756*	0.2834	0.4377*	1.54

(\*) Significant according to Student's t-test for comparison of mean dry weight, root length and height of the respective genotype with the mean of all genotypes under acidic conditions (95% significance level).

**Table 5:** *C. arabica* genotypes selected as tolerant to soil acidity in Andisol after analysis of the treatment effect using the quadrant method and the tolerance index.

GENOTYPE	QUADRANT METHOD	ANDISOL			
		Dry weight (kg)	Root length (m)	Height (m)	TOLERANCE INDEX
E146	4	0.00638*	0.255	0.431*	1.11
Rume Sudan	4	0.00726*	0.3034	0.4303*	0.98
E085	4	0.00528	0.2526	0.3556	1.12
Timor Hybrid	4	0.00645*	0.3037	0.396	1.18

(\*) Significant according to Student's t-test for comparison of mean dry weight, root length and height of the respective genotype with the mean of all genotypes under acidic conditions (95% significance level).

The availability of large germplasm collections in agricultural research centers has allowed for the evaluation of aluminum tolerance, especially in Latin America, where the percentage of acidic soils is high. To this end, several techniques have been developed for the selection of tolerant genotypes for application in breeding programs leading to the production of agricultural varieties that are tolerant to physiological stresses.

With the application of the quadrant method (Figure 1), the International Center for Tropical Agriculture (CIAT) conducted research to obtain varieties that are tolerant to acidity in agricultural crops of economic importance, such as rice, potato, soybean, peanut and cowpea. The dispersion of genotypes across the Cartesian plane quadrants of the model showed that there was variability in the tolerance to acidity in these species, and the progenies within quadrant IV were classified as being tolerant to acid with the potential for high yields (Nicholaides; Piha, 1990). By applying equation (1) with the tolerance index method, genotypes of agricultural species that produce well under high stress conditions can be selected; however, these genotypes still produce much better when lime is applied to eliminate acidity (Howeler, 1990).

Given that there is a coffee germplasm collection in Colombia and that the percentage of acidic soils in the Colombian coffee-growing regions has increased in the last 20 years, the evaluation of a core collection representing the greatest coffee germplasm variability allows for the identification of tolerant genotypes that can be used for the production of varieties with good yields in acidic soils. In this study, the accessions Rume Sudan and Timor Hybrid were selected as tolerant to soil acidity when the seedlings were grown in two types of acidic soils (pH < 5.0) from the Colombian coffee grower region. Timor Hybrid was discovered in 1927 on a traditional coffee plantation; it is a natural hybrid resulting from interspecific crossing between *C. arabica* and *C. canephora* and has been used as a progenitor in several breeding programs because of its resistance to coffee rust (Castillo-Zapata; Moreno-Ruiz, 1988; Alvarado; Posada; Cortina, 2005). Rume Sudan is a semiwild variety from the Marsabit mountains in Sudan (Africa), which is resistant to

coffee berry disease (Agwanda et al., 1997) and has been used as a progenitor in the production of the "centroamericano" variety released in Central America in 2008 (Quijano; Gil, 2009).

Studies conducted in Brazil have evaluated the effect of aluminum (Al<sup>3+</sup>)-induced acidity on the growth of nine commercial coffee varieties. They evaluated the effect of Al<sup>3+</sup> on the growth of the main root in newly germinated seedlings of 26 coffee varieties and found that only the Icatu Vermelho (IAC4045) variety showed levels of tolerance to the acidic condition applied (Braccini et al., 1998; Braccini et al., 2000). These studies were performed with newly germinated seedlings under laboratory conditions using nutrient solutions that simulated acid stress.

The behavior of eight coffee varieties in acidic soils and in lime-corrected soils was evaluated in field Brazilian experiments. Using the same varieties but in hydroponic cultures, the relative tolerance index (RTI) was determined. The varieties tolerant to aluminum under hydroponic conditions corresponded to the varieties tolerant in field experiments (Mistro; Fazuoli; Gallo, 2007).

More recently, the effect of Al<sup>3+</sup> on the seedlings of four coffee varieties grown in nutrient solutions was evaluated, and it was determined that, at least in the initial growth stages, the IAPAR 59 and Catuai amarelo IAC 62 varieties were tolerant to the effects of the acidic conditions, while the Oeiras variety showed intermediate tolerance and the Obatá IAC 1669-20 variety showed sensitivity to aluminum (Macedo et al., 2011).

The cited experiments were conducted with commercial varieties of coffee grown under environmental and edaphic conditions in Brazil, which differ from those of Colombian coffee cultivation. In particular, there have been no reports of the identification of wild *C. arabica* accessions in germplasm banks that may be candidate progenitors for producing genetically improved varieties that are tolerant to soil acidity. This lack of reports suggests that the early selection of genotypes may be an alternative for improvement studies of perennial species, for which obtaining a variety requires approximately 25 years.

This study was limited to the evaluation of the dry mass of plants at 6 months of age, which did not allow for us to determine their agronomic performance in the productive stage. However, it must be taken into account that soil acidity could reduce root growth starting at the juvenile stage, leading to deficiencies in biomass production and a reduction in agricultural productivity (Liang et al., 2013). Genotypes that are selected as tolerant at an early age will probably not be affected in later stages of development, including the productive stage. However, the Rume Sudan and Timor Hybrid genotypes identified in this study as tolerant to acidity in the nursery stage will be grown under the same stress conditions and further evaluated during a production cycle to verify that acid stress has no effect on production. In such cases, these genotypes would be used in genetic crosses with commercial varieties grown in Colombia, with the purpose of initiating a genetic breeding program that would produce a new coffee variety that is tolerant to soil acidity and could be grown by Colombian coffee farmers.

#### 4 CONCLUSIONS

The *Coffea arabica* genotypes used in breeding programs in Colombia differ in their tolerance to soil acidity.

The Timor Hybrid and Rume Sudan genotypes show tolerance to soil acidity. The tolerance of the evaluated genotypes to acidity is independent of the soil type.

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