Productivity of maize genotypes in acid soils of southern Veracruz with and without dolomite

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ABSTRACT

Objective: To determine the effect of soil acidity on the growth and yield of maize genotypes (*Zea mays* L.) under rainfed production conditions, and identify those with greater productive efficiency with and without the application of dolomitic lime.

Design/methodology/approach: Twelve maize genotypes were evaluated in an acidic soil using a randomized complete block design with four replications. Two trials were established: one with dolomitic lime application and one without liming. Plant height, main ear insertion height, and grain yield were recorded. Data were analyzed through individual analyses of variance, mean comparison tests (LSD, $\alpha=0.05$), and correlation analysis. Productive efficiency under limed and non-limed conditions was estimated using the geometric mean index (*GMi*) and the relative efficiency index (*REIi*).

Results: Soil acidity reduced plant height by an average of 7.8%, ear height by 14.4%, and grain yield by 32.9%. SINT 1A and SINT 2B × V540 showed the best adaptation under acidic soil conditions. These same genotypes also exhibited the highest (*GMi*) and (*REIi*) values, indicating the greatest productive efficiency both with and without dolomitic lime application. Under limed soil conditions, V537C × V540 was the most productive genotype, followed by SINT 2B × V540 with acceptable grain yield.

Limitations on study/implications: The evaluation of genotypes was conducted under conditions of soil acidity combined with drought stress, which allowed the identification of genotypes with greater productive efficiency under adverse edaphoclimatic conditions. Multi-environment evaluations and additional cropping cycles are recommended to confirm yield stability.

Findings/conclusions: Soil acidity strongly affected plant architecture and productivity; however, liming improved plant growth and grain yield. SINT 3B × V-540 stood out for its stability and yield, making it a promising option for acidic soils in the Mexican tropics.

Keywords: *Zea mays* L., liming, yield stability, acid tolerance, genotype × environment interaction.

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INTRODUCTION

In southeastern Mexico, particularly in the tropical and subtropical regions of Veracruz, Chiapas, and Oaxaca, maize (*Zea mays* L.) production is carried out mainly under rainfed conditions and with residual soil moisture. These environments have high productive

potential; however, they also present edaphic and climatic constraints that limit grain yield. Among the most important limiting factors is soil acidity, a common characteristic of soils formed under high rainfall conditions (García, 1973). In southern Veracruz, these conditions are widespread, as extensive areas exhibit soil pH values below 5.0, which reduces phosphorus availability, promotes the leaching of base cations (Ca, Mg, and K), and increases the presence of exchangeable aluminum. This, in turn, restricts root growth and nutrient uptake (Zetina-Lezama *et al.*, 2002; Zetina-Lezama *et al.*, 2005. In maize, this type of edaphic stress is associated with reduced vegetative growth, decreases in plant height and ear insertion height, phenological delays, and yield losses that may exceed 70%, depending on the genetic tolerance of the crop and the severity of soil acidity (Dewi-Hayati *et al.*, 2014).

In this scenario, nutrient management is a determining factor. The application of dolomitic lime is a widely used practice to increase soil pH, reduce aluminum toxicity, and improve nutrient availability in the surface horizon (The *et al.*, 2010). Studies conducted in tropical soils have reported significant increases in root development, plant vigor, and yield following dolomite application (Ramírez-Sánchez *et al.*, 2020. However, in rainfed and low-input production systems, this practice is not always feasible for farmers due to the high costs associated with transport and application, as well as the limited capacity to maintain pH correction over the long term (Zetina-Lezama *et al.*, 2005).

Additionally, drought occurrence is common in southern Veracruz under both rainfed and residual moisture conditions, and depending on its intensity and duration, it can significantly affect maize productivity (Zetina-Lezama *et al.*, 2005). A key strategy to increase crop yields under the aforementioned edaphoclimatic conditions is the use of genetic materials adapted to acidic soils and tolerant to drought (Graham, 1984; Sierra *et al.*, 2019; Tandzi *et al.*, 2018).

Within the maize breeding program of the Cotaxtla Experimental Station of the National Institute for Forestry, Agriculture and Livestock Research (INIFAP), hybrids, synthetic varieties, and improved varieties are available that have shown good adaptability in tropical and subtropical areas of southeastern Mexico. In this context, the objectives of the present study were: (1) to determine the agronomic and productive response of 12 maize genotypes (*Zea mays* L.) developed by INIFAP under rainfed conditions, with and without dolomitic lime application, in an acidic soil of southern Veracruz; and (2) to identify materials with better adaptation and productive efficiency under acidic soil conditions.

MATERIALS AND METHODS

Study area

To evaluate the maize genotypes, two field experiments were established during the 2024 summer-autumn growing season in an agricultural field located in the municipality of Juan Rodríguez Clara, Veracruz, Mexico (18° 01’ N, 95° 23’ W; 128 m above sea level), under rainfed conditions. The site is characterized by a warm subhumid climate (Aw_0), with a mean annual precipitation of 1462 mm (García, 1973). The predominant soils are dystrophic Cambisols with a sandy loam texture, characterized by low phosphorus availability and the presence of and interchangeable bases (Zetina-Lezama *et al.*, 2002; 2005).

Liming rate and soil pH determination

Prior to the establishment of the experiment, soil samples were collected from the 0-20 cm layer, and an initial soil pH of 4.6 was determined, indicating a restrictive edaphic condition associated with low fertility. These soil characteristics justified the application of dolomitic lime to improve crop productivity. The liming treatment aimed to increase the original soil pH to approximately 5.4. In the soil where one of the experiments was established, dolomitic lime was applied at a rate of 2.25 t ha^{-1}. This rate was estimated using the equation: $Y = 11.708 - 1.954x$, developed by INIFAP for acidic soils (Zetina *et al.*, 2002); where x corresponds to the dolomitic lime requirement and Y corresponds to the dolomitic lime requirement (t ha^{-1}) needed to reach a soil pH$\geq$5.4, which is considered optimal for maize development (Ruíz *et al.*, 2013). Dolomitic lime was broadcast-applied 15 days prior to sowing and incorporated into the soil with a single disk harrow pass to an approximate depth of 20 cm (Zetina *et al.*, 2017). The second experiment, established in the same soil, was conducted under natural acidic soil conditions, without liming application.

For soil pH determination, composite soil samples were collected in each experiment, consisting of three subsamples per replication, at three stages of the crop cycle: 15 days before sowing (prior to liming), 25 days after sowing, and at physiological maturity. In all samples, soil pH was measured in water using a 1:2 soil-solution ratio with a Hanna potentiometer (model HI9812-51). The values obtained for each replication were averaged to calculate the mean soil pH for each sampling period (Zetina *et al.*, 2017).

Genetic materials

In both experiments, 12 maize genotypes from the INIFAP maize breeding program at the Campo Experimental Cotaxtla were evaluated: H-518, H-520, SINT 1A, SINT 2B, SINT 4B, V-537C, V-540, and five intervarietal crosses derived from materials adapted to the humid tropics: SINT 2B × V-540, SINT 3B × V-540, SINT 4B × V-540, SINT 5B × V-540, and V-537C × V-540 (Sierra *et al.*, 2019).

Experimental design and agronomic management

The experiments were established at a planting density of 62,500 plants ha^{-1}, using a randomized complete block design with four replications. Experimental plots consisted of four rows, each 5 m in length, spaced 0.80 m apart, with the two central rows considered as the effective plot area.

Crop establishment practices, fertilization, weed control, and phytosanitary management were carried out in accordance with INIFAP recommendations for maize production in tropical regions (Palafox *et al.*, 2010).

Explanatory and response variables

During the crop cycle, rainfall at the experimental site was recorded using a plastic rain gauge with a 40-mm capacity and counting ring. Plant height and main ear insertion height were measured in centimeters at the end of the growing cycle. Grain yield was estimated based on the weight of ears harvested from the effective plot, which were shelled and adjusted to a 14% moisture content.

Statistical analysis

Analyses of variance were performed separately for each experiment (with and without dolomitic lime). Mean comparisons were conducted using the Least Significant Difference test (LSD, $\alpha=0.05$). In addition, correlation coefficients between the quantified variables and grain yield were calculated following the procedure described by Olivares (1994).

The yield efficiency of the genotypes under limed and non-limed conditions was estimated using the geometric mean (MG_I):

$$MG_I = \left(Y_{ii} \times Y_{ci}\right)^{1/2}$$

where: Y_{ii} and Y_{ci} correspond to the grain yield of genotype *i* under non-limed and limed conditions, respectively.

Similarly, yield efficiency was also estimated using the relative efficiency index (IER_I)

$$IER_I = \left(\frac{Y_{ii}}{Y_i}\right)\left(\frac{Y_{ci}}{Y_c}\right)$$

where: Y_{ii} and Y_{ci} represent the overall mean grain yield under non-limed and limed conditions, respectively, according to Graham (1984) and Tandzi *et al.* (2018).

Higher values of MG_I and IER_I indicate greater productive efficiency and superior genotype performance across both evaluation environments.

RESULTS AND DISCUSSION

Rainfall and soil pH dynamics during the crop cycle

Although total accumulated rainfall during the crop cycle reached 772 mm (310 mm from sowing to flowering and 462 mm from flowering to crop maturity), a level close to that considered optimal for adequate maize development (Kranz *et al.*, 2008), its distribution was irregular in both timing and amount. Periods of drought occurred during the cycle and affected the yield of the genotypes in both experiments. Consequently, the results of this study reflect the combined effect of soil management conditions (with and without liming) and drought occurrence, which is common in this maize-producing region.

Regarding soil pH, the incorporation of dolomitic lime increased the initial value from 4.9 to 5.4 by the end of the crop cycle, evidencing the positive effect of liming on the neutralization of soil acidity. However, the temporal dynamics of soil pH showed a more pronounced increase during the vegetative development of maize (pH 6.6), whereas under non-limed conditions, soil pH values remained relatively stable throughout the crop cycle (Figure 1).

Response of plant height and ear insertion to liming in acidic soil

Genotypes that showed greater stability in plant height also tended to maintain a more uniform ear insertion across environments. Under dolomitic lime application (CD), significant differences among genotypes were observed for both plant height and ear insertion height (Table 1). The highest values for both traits were recorded in genotypes such as V-537C × V-540, SINT 4B × V-540, and SINT 3B × V-540, which were consistently grouped in the upper statistical category, indicating a positive response to liming and a greater capacity to take advantage of the chemical correction of acidic soil.

Under non-limed conditions (SD), V-540 stood out compared to the other genotypes, followed by SINT 2B × V-540 and SINT 5B × V-540, which maintained relatively high values for both plant height and ear insertion height. These genotypes showed a lower relative reduction under uncorrected soil acidity.

The analysis of percentage reduction between environments with and without dolomite allowed the identification of consistent patterns of stability and sensitivity. V-540, SINT 2B × V-540, and SINT 5B × V-540 exhibited the lowest reductions in both traits (≤6%), standing out as the most stable genotypes under soil acidity conditions. In contrast, materials such as SINT 3B × V-540, SINT 4B × V-540, and V-537C × V-540 showed parallel and pronounced reductions, particularly in ear insertion height, indicating a greater dependence on liming to express their morpho-agronomic potential.

Overall, the coordinated response of plant height and ear insertion height reflects the close link between vegetative vigor and reproductive development in maize grown under acidic soil conditions. The contrasting stability patterns among genotypes suggest

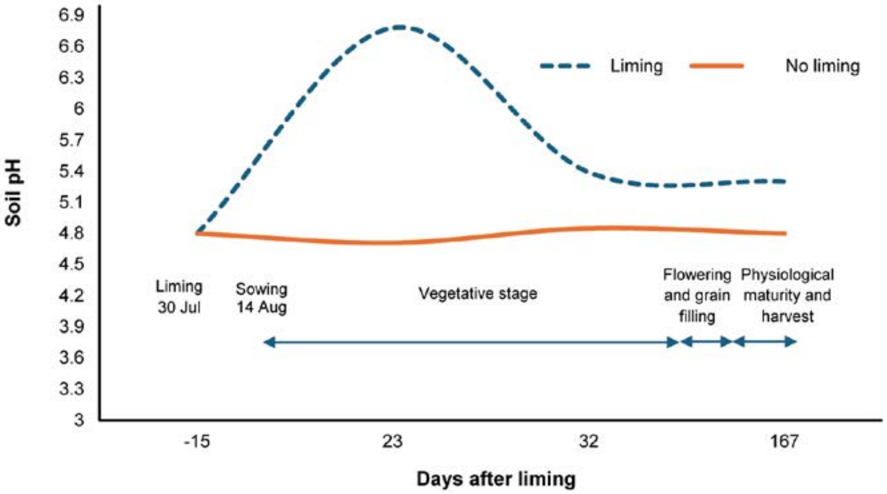

Figure 1. Soil pH dynamics in a dystrophic Cambisol under limed and non-limed conditions during the maize cropping cycle in Juan Rodríguez Clara, Veracruz.

Table 1. Effect of acidic soil stress on plant height and ear insertion height of maize genotypes evaluated under conditions with and without dolomitic lime application. Juan Rodríguez Clara, Veracruz, Mexico. Summer-autumn growing season, 2024.

Genotype	AP (cm)		AP Reduction (%)	AM (cm)		AM Reduction (%)
	CD	SD		CD	SD	
H-518	149.80cde	143.00ab	4.53	71.50de	59.43ef	16.90
H-520	146.45e	148.58ab	1.48	69.08e	63.50def	8.08
SINT 1A	153.33b-e	139.70bc	8.91	84.00ab	67.35cde	19.84
SINT 2B	156.98a-e	146.83ab	6.48	79.20a-d	66.08def	16.53
SINT 2B × V-540	162.08a-e	152.50ab	5.91	80.15a-d	74.93abc	6.55
SINT 3B × V-540	166.13abc	147.50ab	11.21	87.83a	67.85cde	22.77
SINT 4B	147.30de	126.75c	13.95	72.43cde	58.68f	18.99
SINT 4B × V-540	167.83ab	147.68ab	11.99	81.93abc	65.75def	19.74
SINT 5B × V-540	159.58a-e	150.00ab	6.01	76.95b-e	76.58ab	0.43
V-537C	161.20a-e	148.40ab	7.93	81.63abc	67.28cde	17.61
V-537C × V-540	172.38a	149.68ab	13.17	86.93a	70.25bcd	19.21
V-540	164.33a-d	155.33a	5.48	85.58ab	80.03a	6.52
Mean	158.95	146.33	7.84	79.76	68.14	14.43
DMS (0.05)	17.669	13.133		9.7643	8.4775	
Correlation with yield	0.247 ns	0.284 ns		0.334 ns	0.214 ns	

AP=Plant height. AM=Ear insertion height. With dolomitic lime application (CD). Without dolomitic lime application (SD). Correlation coefficient with grain yield. Different letters within columns indicate significant differences (LSD=0.05).

differences in physiological efficiency to sustain growth under edaphic stress, likely associated with tolerance to Al^{3+} toxicity and with Ca and Mg availability. In this context, both traits emerge as early and reliable indicators of genotypic adaptation to soil acidity (Kochian *et al.*, 2015).

Effect of liming on grain yield in maize genotypes

Regarding grain yield, the analysis of variance revealed a strong response to liming, with significant differences among genotypes both in achieved yield levels and in the magnitude of yield reduction under uncorrected soil acidity. Some materials maintained relatively high yields across both environments, whereas others relied heavily on dolomitic lime application to fully express their productive potential (Table 2), confirming the existence of genetic variability in the response to soil acidity and its correction through liming.

Under non-limed conditions, higher coefficients of variation and larger error mean squares were observed, reflecting greater yield instability associated with Al^{3+} toxicity stress and reduced availability of basic cations. This response pattern has been widely documented in maize cultivated on acidic soils (von Uexküll & Mutert, 1995; The *et al.*, 2010; Lestari, 2016; Chairiyah, 2020).

With dolomitic lime application, grain yields ranged approximately from 2,400 to 3,700 kg ha^{-1} (Table 3). The highest values were recorded for V-537C × V-540, SINT

Table 2. Mean squares and statistical significance of the variables measured in maize trials conducted on acidic soil, with and without dolomitic lime application.

SV	df	AP	AM	Grain yield
Dolomitic lime application (CD)				
Treatments	11	278.48 ns	153.05**	576977.33**
Blocks	3	969.93	423.55	64820.29
Error	33	150.84	46.07	65115.248
Total	47			
CV (%)		7.73	8.51	8.86
No dolomitic lime application (SD)				
Treatments	11	216.29**	167.78**	298013.51**
Blocks	3	743.38	295.18	226268.7
Error	33	83.33	34.73	87094.97
Total	47			
CV (%)		6.24	8.65	15.48

SV=source of variation. df=degrees of freedom. AP=plant height. AM=ear insertion height. CV=coefficient of variation.**significant at 0.01. *significant at 0.05. ns=not significant.

Table 3. Mean grain yield of maize genotypes evaluated under acidic soil conditions, with and without dolomitic lime application, and estimated selection indices.

Genotype	Grain yield (kg ha^{-1}) with dolomite	Grain yield (kg ha^{-1}) without dolomite	*MGi*	*IERi*
H-518	2645.70def	1646.90cd	2087.39	0.794
H-520	2386.00f	1900.90a-d	2129.68	0.826
SINT 1A	3084.20bc	2320.30a	2675.09	1.303
SINT 2B	2935.50bcd	1550.90d	2133.7	0.829
SINT 2B × V-540	3141.20b	2316.70a	2697.6	1.325
SINT 3B × V-540	3008.50bcd	2226.30ab	2587.95	1.22
SINT 4B	3147.00b	1560.00d	2215.73	0.894
SINT 4B × V-540	2403.00f	2064.70abc	2227.45	0.904
SINT 5B × V-540	2808.30b-e	1780.10cd	2235.83	0.911
V-537C	2509.50ef	1795.70cd	2122.76	0.821
V-537C × V-540	3719.90a	1909.50a-d	2665.12	1.294
V-540	2772.60cde	1803.40bcd	2236.11	0.911
Mean	**2880.12**	**1906.28**	**2334.53**	**1.003**

Genotypes with different letters within each grain yield column are statistically different (LSD=0.05).

4B, and SINT 2B × V-540, which consistently ranked within the upper statistical group, indicating a strong responsiveness to the partial neutralization of soil acidity. In contrast, under non-limed conditions, yields declined across genotypes, ranging from approximately 1,500 to 2,300 kg ha^{-1}, a reduction that was also influenced by the occurrence of terminal drought. Nevertheless, SINT 2B × V-540, SINT 1A, and SINT 3B × V-540 maintained comparatively higher yields under uncorrected acidic soil conditions.

The average yield reduction between environments was close to 33%, although marked contrasts among genotypes were observed. SINT 4B × V-540 exhibited a moderate reduction (≈14%), standing out as the most stable material, whereas V-540 showed an intermediate reduction. In contrast, SINT 4B, H-518, H-520, V-537C × V-540, and SINT 2B showed the greatest yield losses, highlighting their strong dependence on liming to express their productive potential. This pattern is consistent with reports for maize cultivated on acidic soils, where yield losses associated with Al^{3+} toxicity typically range between 20 and 50% (The *et al.*, 2010; Lestari, 2016).

The results confirm that liming significantly increases grain yield in acidic soils (Chairiyah *et al.*, 2020); however, the magnitude of the response depends on the degree of genetic adaptation of each material. The coexistence of genotypes that are stable under uncorrected soil acidity and others that respond strongly to pH correction underscores the need to implement selection strategies tailored to specific edaphic conditions and, where appropriate, to assess the feasibility of using soil amendments in production systems to improve productivity (Ramírez-Sánchez *et al.*, 2020).

Productive efficiency of genotypes under contrasting soil acidity conditions

The geometric mean allowed the identification of genotypes with greater yield stability across contrasting environments, by penalizing those materials that exhibit high performance under favorable conditions but suffer sharp yield reductions under stress. Genotypes SINT 2B × V-540, SINT 1A, and SINT 3B × V-540 stood out by presenting geometric mean values above the overall average, indicating better adaptation under both limed and uncorrected acidic soil conditions. This response is particularly desirable for the selection of materials intended for regions with persistent soil acidity. In contrast, genotypes such as H-518 and SINT 4B showed low geometric mean values, reflecting greater susceptibility to edaphic stress.

The relative efficiency index complemented the stability analysis by integrating the relative performance of genotypes across both environments. Values of greater than 1 indicated productive performance above the general mean. In this context, SINT 2B × V-540, SINT 1A, and V-537C × V-540 exhibited the highest values, reflecting a favorable combination of high yield and stability under soil acidity conditions. Conversely, H-518 and SINT 4B recorded index values below unity, confirming their limited performance in edaphically restrictive environments.

The geometric mean and the relative efficiency index consistently discriminated genotypes with stable performance under edaphic stress. The agreement between both indicators confirmed the identification of materials capable of maintaining grain yield under acidic soil conditions, which is consistent with previous reports highlighting the combined use of stability and efficiency metrics for selecting maize genotypes in soils with chemical limitations (Ochoa-Cadavid *et al.*, 2019; Tirado-Soto *et al.*, 2019).

Relationship between plant architecture and grain yield under soil acidity

Correlation analysis between plant height, ear insertion height, and grain yield showed low and non-significant associations under both soil conditions (Table 1). This indicates that, although soil acidity affects plant architecture, these variations do not necessarily translate proportionally into differences in grain yield. The low magnitude of the correlations suggests that yield performance under acidic stress is governed by a more complex set of physiological traits, likely associated with aluminum tolerance, nutrient use efficiency, and stability of grain filling (Kochian *et al.*, 2015).

CONCLUSIONS

Soil acidity significantly reduced plant height, ear insertion height, and grain yield in most of the evaluated genotypes, confirming the high sensitivity of maize to aluminum toxicity and low availability of phosphorus and exchangeable bases under acidic soil conditions.

Within the evaluated set, the genotypes SINT 2B × V-540, SINT 1A, V-537C × V-540, and SINT 3B × V-540 exhibited favorable performance in terms of productivity and stability under contrasting acidity conditions, positioning them as promising alternatives for cultivation in regions where soil acidity is a recurrent constraint. Additionally, the wide variability observed among genotypes indicates substantial potential for continued selection toward acid tolerance and for the identification of materials with broad adaptation.

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