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Effect of liming on forage yield and profitability of INIAP 543 – QPM corn in an Andisol soil in Ecuador

Efecto del encalado en el rendimiento forrajero y rentabilidad del maíz INIAP 543 – QPM en un suelo andisol de Ecuador

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ABSTRACT

Forage corn is essential for ruminant production; however, the acidity of the soil significantly reduces its productivity. The aim of this work was to evaluate the effect of liming on the forage yield and profitability of INIAP 543 – QPM corn grown in an andisol soil of Santo Domingo de los Tsáchilas, Ecuador. Four treatments consisting of three doses of dolomite (1.0, 1.5 and 2.0 t ha^{-1}) and a control treatment without lime were evaluated. The variables recorded were green matter yield, final soil pH and net economic profit. Liming had a significant impact ($p<0.05$) on green mass yield and final soil ph. The dose of 1.5 t ha-1 of dolomite showed the greatest increase in green matter yield. All liming doses succeeded in raising pH above 5.5, which is necessary to precipitate Al^{3+}. The 1.5 t ha^{-1} dose of dolomite resulted in the greatest net economic profit from liming. In conclusion, the 1.5 t ha^{-1} dose of dolomite lime is agronomically and economically viable to enhance corn forage production on acid andisol soil.

Palabras clave: economic benefit; soil liming; forage yield; acidic soil; *Zea mays*

RESUMEN

El maíz forrajero es indispensable para la producción de rumiantes; sin embargo, la acidez del suelo reduce significativamente su productividad. El objetivo del trabajo fue evaluar el efecto del encalado en el rendimiento forrajero y rentabilidad del maíz INIAP 543 – QPM cultivado en un suelo andisol de Santo Domingo de los Tsáchilas, Ecuador. Se evaluaron cuatro tratamientos conformados por tres dosis de dolomita (1,0; 1,5 y 2,0 t ha^{-1}) y un tratamiento control sin cal. Las variables evaluadas fueron rendimiento de materia verde, pH final del suelo y beneficio económico neto. El encalado tuvo un impacto significativo ($p<0,05$) en el rendimiento de materia verde y el pH final del suelo. La dosis de 1,5 t ha^{-1} de dolomita mostró los mayores incrementos en rendimiento de materia verde. Todas las dosis de encalado lograron elevar el pH por encima de 5,5, necesario para precipitar el Al3+. La dosis de 1,5 t ha^{-1} de dolomita logró la mayor rentabilidad económica. En conclusión, la dosis de 1,5 t ha^{-1} de dolomita fue agronómica y económicamente viable para potenciar la producción forrajera de maíz en suelo andisol ácido.

Keywords: beneficio económico; encalado del suelo; rendimiento de forraje; suelo ácido; *Zea mays*

1. INTRODUCTION

In recent years, corn production has increased by more than 118% worldwide as increased consumption and technological advances have encouraged an expansion of the productive area by more than 46% and an improvement in yield of close to two tons in the last 25 years. It is currently the largest cereal in terms of production volume (1,137 million tons) and, in the 2030s, it is projected to become the main crop and tradable crop in all agricultural sectors (Erenstein et al., 2022).

For Ecuador, corn represents a crop of food, of social and economic importance, since it is a source of energy, employment and a driving force for the agricultural and agro-industrial economy (Analuisa Aroca et al., 2020). For fresh consumption and animal feed as fodder, high-protein white corn cultivars have been developed (Limongi Andrade et al., 2019).

The main problem of the crop remains the low productivity (5.76 t ha-1), where climatic variability, soil acidity, high incidence of pests and diseases, and limited irrigation and fertilization technology are the main factors reducing productivity (Cavache Ulloa, 2016; Blackmore et al., 2021; MAG, 2022; INEC, 2024).

Andisols are typical acidic soils developed from volcanic materials that cover around 1% of the Earth's surface, distributed across all continents except Antarctica. They present characteristics associated with Al-humus complexes, with strong acidity and a high content of the exchangeable Al^{3+} ion, which is toxic to crops. However, the aftermath of volcanic eruptions gives rise to the most productive soils in the world and hence their importance in global food security (Fiantis et al., 2019; Takahashi, 2020).

In Ecuador, 30% of the national territory corresponds to acidic andisol soils. These are distributed throughout the central-northern Highland region, in the humid areas of the Andean foothills, part of the coast, and the Amazon (Calvache, 2014; Silva et al., 2021).

In humid tropical areas such as Santo Domingo de Los Tsáchilas, andisol soils suffer continuous losses of bases such as Ca^{2+}, $Mg^{2}+$, and K^{+}, due to leaching caused by heavy rainfall, which generates nutrient imbalance, since the sites left by Ca^{2+}, Mg^{2+} and K^{+} in the exchange zone are replaced by H^{+} and Al^{3+}, which contribute to increasing acidity. In addition, they contain high levels of allophane clay, which has a high capacity to fix P and decreases its availability for plants (Takahashi, 2020; (Mihai et al., 2023).

To improve soil pH, and basic cation concentrations and reduce toxicity caused by hydrogen and aluminum, the practice of liming is widely recommended. This consists of applying alkaline reaction materials such as calcite ($CaCO_3$), magnesite ($MgCO_3$), dolomite [$CaMg(CO_3)_2$], slaked lime [$Ca(OH)_2$] and quicklime (CaO), with a high acidity neutralization power and contribution of cations that improve the exchange capacity and therefore its chemical fertility (Li et al., 2019; Enesi et al., 2023).

However, lime has low solubility and mobility in the soil profile when it is applied superficially in direct seeding systems and is not incorporated. This fact has led to the recommendation of mixing with agricultural gypsum ($CaSO_4$ $2H_2O$) given the solubility of the latter, which is about 170 times greater than that of lime, which increases the mobility of basic cations (Ca^{2+}, Mg^{2+} and K^{+}) in deeper layers, and when the S-SO_4^{2-} dissociates, it binds to the exchangeable Al^{3+}, decreasing its activity and toxic effect on plants (Crusciol et al., 2016; Crusciol et al., 2019).

In this context, previous research has demonstrated the effectiveness of liming in reducing the negative impact of acidity and boosting corn production in acidic soils, where previous experiences have described yield improvements of more than 60% and others even greater than 100% compared to control treatments without liming (Crusciol et al., 2019; Agegnehu et al., 2021).

Since much of Ecuador's livestock production is located in humid tropical areas, where acidic andisols prevail, and there is a growing trend to use forage corn to supplement ruminant feed, soil acidity becomes limiting for the production of forage corn and, consequently, for livestock. This does not allow producers to achieve profitable yield goals due to the limited information available on limiting recommendations for corn. Therefore, the objective of the research was to evaluate the effect of liming on the forage yield and profitability of INIAP 543 – QPM corn in an andisol soil in Ecuador.

2. MATERIALS AND METHODS

2.1. Location

The research was carried out during the dry season of 2022 (August to November) and the rainy season of 2023 (January to April), at the Mishilí farm of the Tsa'chila Higher Technological Institute, located at km 6 ½ of the Santo Domingo - Quevedo road, in the province of Santo Domingo de los Tsáchilas, Ecuador.

The experimental site was geographically located at UTM coordinates X: -0.300611 and Y: -79.207587 (Figure 1), at an altitude of 585 meters above sea level. The average annual temperature, precipitation, sunlight, and relative humidity were 24.9 °C, 3052 mm, 780 hours year-1, and 87.3%, respectively.

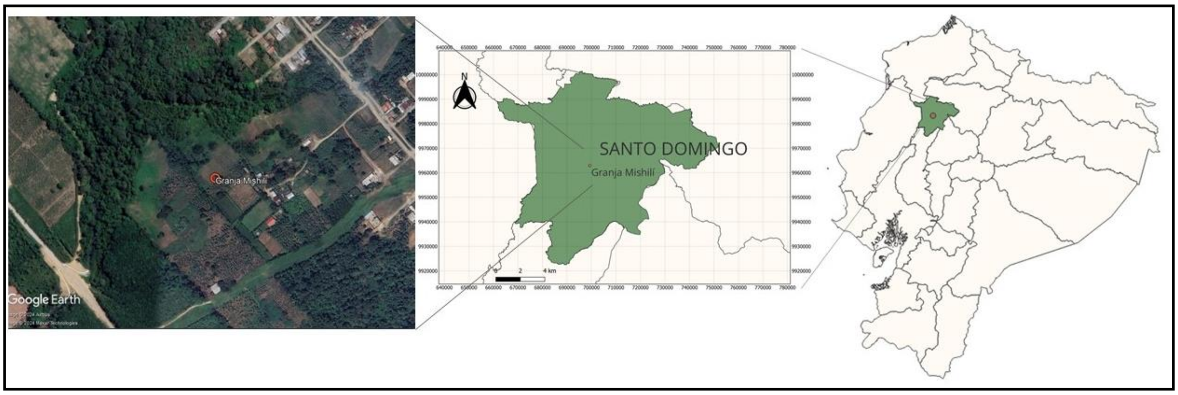

Figure 1. Geographic location of the experimental site

In Santo Domingo de los Tsáchilas, according to several studies, soils of volcanic origin with the presence of amorphous clays such as allophane prevail, which is why they are classified as acidic Andisols (Abril et al., 2020; Silva-Yumi et al., 2021).

Before the experiment, a soil sample was taken from the experimental site at a depth of 0.20 m, which was sent to the laboratory to determine the chemical characteristics, the results of which are detailed in Table 1.

Table 1. Chemical characteristics of the soil of the experimental site before the establishment of the experiment. Santo Domingo, Ecuador

pH	MO	NH_4	P	S	K	Ca	Mg	A+H
	%	------------ mg kg^{-1} -----------			--------------- $cmol_c$ kg^{-1} ---------------			
5,07	2,25	24,10	11,21	9,62	0,22	4,14	0,71	0,89

2.2. Plant material

The synthetic white corn cultivar INIAP 543 – QPM, open-pollinated, was used. It was created by the corn program of the Portoviejo Experimental Station of the National Institute of Agricultural Research – INIAP. The cultivar was developed and released in 2019 for fresh consumption as corn, for industrial use, and forage due to its high protein quality (Limongi Andrade et al., 2019).

2.3. Treatments, design, and experimental unit

The treatments evaluated were three levels of dolomite lime [$CaMg(CO_3)_2$]: T1: 1.0 t ha^{-1}, T2: 1.5 t ha^{-1}, T3: 2.0 t ha^{-1} and T4: control treatment without liming. The dolomite lime was composed of 46% CaO and 12%

MgO, with a particle size of 100 mesh. In addition, due to the low solubility and mobility of dolomite lime in soils under the direct seeding system, it was decided to add agricultural gypsum ($CaSO_4 2H_2O$) to all lime doses in a proportion of 3:1, that is one part of gypsum for every three parts of lime. This is according to what was described by Espinosa & Molina (1999).

Based on the above, the gypsum doses were 333, 500, and 666 kg ha-1, for the dose of 1.0, 1.5, and 2.0 t ha^{-1} of dolomite lime, respectively. The agricultural gypsum used was of 100 mesh particle size, and its composition was 18% S and 26% CaO.

A randomized complete block design (RBD) was used with four treatments, three replicas, and 20 experimental units. The experimental unit consisted of 24 m^2 plots with six rows of plants spaced 0.80 m apart and 0.25 m between plants. The liming was applied 30 days before sowing, which was directed to the sowing line in a 0.30 m wide band.

2.4. Response variables and data analysis

2.4.1. Growth components

- Plant height (m) was measured at the time of male flowering, using a measuring tape from ground level to the flag leaf.
- Stem diameter (mm) was recorded at the time of male flowering, which was done at ground level using a caliper.
- Leaf area (m^2) was recorded at the R1 phenological stage using the methodology proposed by Razquin et al. (2017), for which the equation [1] was used for calculation [1]:

$$AF_p = AF_{MD} * \left(\frac{NH_{obs}}{NH_{msx}}\right) * \left(\frac{AFesp_{obs}}{AFesp_{MD}}\right) \quad [1]$$

- Where AFp is the estimated leaf area of each plant from the measurement of: i) said individual plant: NHobs (number of green leaves), AFespobs (leaf area of the ear leaf), and ii) of the reference population of each treatment: NHmax (maximum number of green leaves per plant observed), AFespMD (leaf area of the ear leaf) and AFMD (average AFp obtained in destructive sampling).
- The dry weight of roots (g) was recorded at the phenological stage R1, according to the methodology described by Pérez López, et al. (2013), where the roots of three plants taken at random from the center of the plot were washed, taken to the laboratory and placed to dry in a forced air oven at 80°C until reaching constant weight.

2.4.2. Yield components

The green matter yield (t ha-1) was recorded 70 days after sowing, at the R3 phenological stage (milky grain). To record the data, an area of 2 m2 was marked in the center of each experimental plot, from where all the plants were extracted, including the cobs, which were crushed in a grass chopper, where the green weight in kg was recorded, and with this data, the yield per hectare was estimated.

The dry matter yield (t ha^{-1}) was also taken 70 days after sowing (stage R3), for which three samples of crushed green matter of 100 g were taken from each experimental plot, which were taken to the laboratory and placed in a forced air oven at 80°C until achieving constant dry weight. With the dry weight data, the dry matter yield per hectare was estimated.

2.4.3. Soil pH and nutrient concentration in leaf tissue

The concentration of macronutrients in leaf tissue was evaluated 70 days after sowing (stage R3), for which a sample consisting of twelve random leaves (subsamples) located under the cob was taken from the center of the experimental plot, following the methodology of Correndo & García (2012). These leaves were sent to the soil, water, and tissue laboratory of the Polytechnic Agricultural School of Manabí, where the determinations of macronutrients were carried out by dry digestion and total nitrogen by the Kjeldahl method.

To record the final soil pH, five soil subsamples were collected from each experimental unit at a depth of 0.20 m, taken within the sowing line with the help of an auger. The subsamples were mixed homogeneously in a clean plastic container, avoiding touching the soil with the hand to avoid alteration of the sample. One kg of the homogeneous sample was then placed in a ziplock plastic bag, labeled with a marker, and sent to the laboratory, where pH determinations were performed in a soil-H2O ratio with a volume of 1:2.5.

2.4.4. Com Economic component

The economic analysis of the treatments was estimated using algebraic expressions applied by Ayvar-Serna et al. (2020), where the total cost (TC) is estimated by adding the fixed costs (FC) plus the variable costs (VC), (TC = FC+VC). To quantify the total income (TI), the income obtained from the sale of products was calculated according to the formula: TI = PV*Ren, in which: PV is the sale price of green forage (USD/40 kg bag), and Ren is the yield per hectare (40 kg bags of forage). The net income (NI) is the result of subtracting the total income less the total expenses (NI = TI - CT). The benefit-cost ratio or return per dollar invested (RBC) is obtained by dividing the net income by the total expenses (RBC = IN/CT).

The recorded data were analyzed using ANOVA and separation of means with Tukey's test ($\alpha = 0.05$). The statistical package used was InfoStat Professional Version 2020.

2.5. Specific management of the experiment

Before sowing, the seeds were treated with imidacloprid + thiodicarb at a dose of 25 mL kg^{-1} of seeds. At 10 days after sowing (DAS), the insecticide thiamethoxam was applied as a “drench” at a dose of 1 mL L^{-1} of water. Based on the monitoring of insect vector populations (leafhoppers, aphids, thrips, and beetles), fipronil was applied at a dose of 0.7 mL L^{-1} of water 30 days after sowing.g

Two controls of the armyworm were carried out, the first at 20 days after sowing with the insecticide Spinetoram at a dose of 0.5 mL L^{-1} of water, while the second was carried out at 45 days after sowing with the insecticide Lufenuron at a dose of 1.5 mL L^{-1} of water.

Pre-emergence weed control was carried out with a mixture of the herbicides Atrazine-80 + Pendimethalin at doses of 1.5 + 3.0 L ha^{-1}, respectively, of each product. For post-emergence weed control, MCPA was applied at a rate of 0.75 L ha^{-1}, plus the herbicide nicosulfuron at a rate of 50 g ha^{-1}. Post-emergence application was carried out when the weeds had between one and three leaves.

Fertilization was determined based on soil analysis, crop demand, and previous fertilization experiences in the area. The fertilization dose was 100 kg of nitrogen, 46 kg of phosphorus, 100 kg of potassium, and 50 kg of sulfur. Ammonium sulfate was used as a source of sulfur and nitrogen, diammonium phosphate for phosphorus, potassium muriate for potassium, and ammonium nitrate as a source of nitrogen.

Fertilizers were applied based on the phenological stages, where according to studies by García and Espinosa (2009), the greatest nutritional demand and agronomic response of tropical corn to fertilization occurs. In this context, nitrogen was applied in three fractions: 20% in the phenological stage of emergence (VE), 40% in the stage of leaf six (V6), and the remaining 40% in the stage of leaf 10 (V10). Phosphorus was placed in its entirety at the time of emergence (VE). Potassium was applied 50% of the dose in the emerging stage (VE) and the remaining 50% in the stage of leaf six (V6).

In the dry season, supplementary irrigation was carried out by sprinkling, performing the irrigation for 10 weeks until completing 70 days after sowing, which was when the harvest was carried out and the evaluations were made. Two weekly irrigations were carried out. In the first week, a 15 mm irrigation sheet was placed. In the second and third weeks, a 21 mm irrigation layer was applied. In the fourth and fifth weeks, 30 mm of irrigation was applied. In the sixth and seventh weeks, a 42 mm irrigation layer was placed. In weeks eight, nine, and ten, the irrigation layer was 56 mm.

3. RESULTS AND DISCUSION

3.1. Growth components

Plant height and stem diameter were significantly affected ($p<0.05$) by the different levels of dolomite tested in the 2022 and 2023 seasons. It was observed that the doses of 1.5 and 2.0 t ha^{-1} were statistically similar and tended to promote greater growth compared to the lowest level of dolomite and the control treatment that did not receive liming (Table 2).

Table 2. Effect of three levels of dolomite on height and stem diameter of corn in an acidic andisol soil

Dolomite levels [$CaMg(CO_3)_2$]	Dry season 2022		Rainy season 2023	
	Plant height (cm)	Stem diameter (mm)	Plant height (cm)	Stem diameter (mm)
1,0 t ha^{-1}	2,03 b[1/]	24,20 b	2,08 ab	27,38 a
1,5 t ha^{-1}	2,25 a	27,11 a	2,24 a	27,51 a
2,0 t ha^{-1}	2,27 a	25,73 ab	2,22 a	27,03 a
Control	1,84 c	21,62 c	1,95 b	23,11 b
p-valor ANOVA	0,0047	0,0001	0,0042	0,007
C.V. %	4,83	5,97	2,94	5,82

[1/] Means within columns with different letters differ statistically according to the Tukey test (α = 0,05)

The plant height results achieved were close to those obtained by Devkota et al. (2019) y Chairiyah et al. (2021) who reported greater plant height in the control treatment without lime, and similar plant heights between doses of 1.5 to 2.0 t ha^{-1} of lime, so, from an optimization point of view, 1.5 t ha^{-1} may be sufficient to enhance corn growth. It was not possible to compare the stem diameter results with other authors, due to the limited information available on this variable under the effect of liming.

The liming treatments had a significant impact ($p<0.05$) on leaf area and root dry mass during the 2022 and 2023 seasons. The three doses of dolomite applied presented statistically similar averages to each other, although significantly different from the control treatment without lime (Table 3).

During the 2022 dry season, the 1.5 t ha^{-1} dose of dolomite achieved the greatest increase in leaf area and root dry mass, with 29.23 and 22.98%, respectively, compared to the control treatment without liming (Table 3).

Similarly, for the 2023 rainy season, where the 1.5 t ha^{-1} dose of dolomite lime achieved the greatest increase in leaf area and root dry mass, with 20.29 and 34.18%, respectively, over the control treatment without lime (Table 3).

Table 3. Effect of three levels of dolomite on leaf area and dry root mass of corn in an acidic andisol soil

Dolomite levels [$CaMg(CO_3)_2$]	Dry season 2022		Rainy season 2023	
	Leaf area (m^2)	Root dry mass (g)	Leaf area (m^2)	Root dry mass (g)
1,0 t ha^{-1}	0,61 a[1/]	16,50 a	0,64 a	19,13 ab
1,5 t ha^{-1}	0,65 a	17,19 a	0,69 a	21,36 a
2,0 t ha^{-1}	0,62 a	16,60 a	0,67 a	20,45 a
Control	0,46 b	13,24 b	0,55 b	14,06 b
p-valor ANOVA	0,0001	0,0127	0,0039	0,0030
C.V. %	5,49	10,60	9,30	13,23

[1/] Means within columns with different letters differ statistically according to the Tukey test (α = 0,05)

In the 2023 rainy season, the leaf area and root dry mass averages tend to increase about the 2022 dry season in all treatments (Table 3), which could be because the root holes left by the first planting cycle facilitate greater exploration of the soil by new roots. In addition, the higher humidity resulting from rainfall and ambient temperature typical of the season can contribute to greater plant growth, expressed in increases in root mass and leaf area.

Although the dose of 1.5 t ha^{-1} of lime was the one that achieved the greatest numerical increase in leaf area and root dry mass, from a statistical and optimization point of view, the dose of 1.0 t ha^{-1} of lime would be sufficient to promote good leaf and root development in corn plants (Table 3).

The above coincides with the results described by Kasno et al. (2023), who reported statistically similar effects between doses of dolomite lime of 1.0, 1.5, and 2.0 t ha^{-1} for the dry mass of corn plants including the roots, where they conclude that doses of 1.0 t ha^{-1} of lime would be appropriate to stimulate general plant growth in an acidic tropical soil.

Regarding leaf area, the results achieved are close to those reported by Victoria et al. (2019) y Tabri et al. (2021), who achieved significant increases in the number of leaves, leaf area, and leaf area index, in corn plants treated with lime doses of 500 to 600 kg ha^{-1}, compared to control treatments without lime.

3.2. Yield components

Liming treatments had a positive and significant impact ($p<0.05$) on green and dry matter yield during the dry and rainy seasons of 2022 and 2023, respectively (Table 4). In the dry season of 2022, the 1.5 and 2.0 t ha^{-1} dolomite treatments achieved statistically similar green and dry matter yields, with the 1.5 t ha^{-1} dose achieving the maximum increase in green and dry matter yield, with 36.78 and 46.31%, concerning the control treatment, respectively (Table 4).

A similar situation was observed for the 2023 rainy season, for the doses of 1.5 and 2.0 t ha^{-1}, which were statistically similar, but with a higher numerical average for the 1.5 t ha^{-1} dose, which achieved increases of 36.70 and 51.92 % for green and dry matter yield in their respective order, about the control treatment without liming (Table 4). In the 2023 rainy season, a higher yield of green and dry matter is observed in the 2022 dry season, in all treatments, although it is more evident in treatments with lime (Table 4).

This fact could be due to the warmer and more humid climatic conditions typical of the rainy season, which promote greater physiological activity in the plant, which is expressed in greater biomass accumulation.

Table 4. Effect of three levels of dolomite on green and dry matter yield of corn in an acidic andisol soil

Dolomite levels [$CaMg(CO_3)_2$]	Dry season 2022		Rainy season 2023	
	Green matter yield (t ha^{-1})	Dry matter yield (t ha^{-1})	Green matter yield (t ha^{-1})	Dry matter yield (t ha^{-1})
1,0 t ha^{-1}	44,75 b[1]	11,37 b	47,27 b	14,64 b
1,5 t ha^{-1}	47,74 a	13,69 a	50,06 a	16,41 a
2,0 t ha^{-1}	47,56 a	13,52 a	49,12 ab	15,76 ab
Control	30,18 c	7,35 c	31,69 c	7,89 c
p-value ANOVA	0,0067	0,0069	0,0001	0,0005
C.V. %	11,2	14,03	7,13	9,65

1/ Means within columns with different letters differ statistically according to the Tukey test ($\alpha = 0,05$)

The yield results achieved are similar to those described by Kasno et al. (2023) in acidic soils of Indonesia, who reported a significant increase in maize yield with liming doses of 0.5, 1.0, 1.5, and 2.0 t ha^{-1} of lime, compared to the control treatment, where the maximum grain yield (11.07 t ha^{-1}) was achieved with 1.5 t ha-1 of lime, but the maximum dry biomass yield was achieved with 1.0 t ha^{-1} of lime.

In this same context, Devkota et al. (2019) reported that 1.5 t ha^{-1} of lime was the most appropriate dose to maximize maize yield in the acidic soils of Khumaltar, Nepal. Our results are also close to those obtained by

Chairiyah et al. (2021) in acidic soils of Sumatra, Indonesia, who reported that the highest biomass production and corn grain yield was achieved with lime doses between 1.0 to 2.0 t ha^{-1}, so the dose of 1.5 t ha^{-1} obtained in our results is located in those ranges.

At the local level, the dose of 1.5 t ha^{-1} of dolomite lime has also been reported as the most optimal for pineapple cultivation in acidic Andisol soils of Santo Domingo de los Tsáchilas, Ecuador (Mite et al., 2009). These findings confirm the veracity of the results achieved with the dose of 1.5 t ha^{-1} of dolomite lime, to enhance the yield of forage corn.

3.3. Soil pH and nutrient concentration in leaf tissue

The dolomite levels analyzed had a significant impact ($p<0.05$) on the final soil pH in the dry season of 2022 and the rainy season of 2023. All dolomite levels managed to increase the soil pH above 5.5 (Figure 2), which, according to various authors, is considered ideal for precipitating Al3+ in acidic tropical soils. Levels below this threshold favor the solubilization of Al^{3+} in the soil solution, which is phytotoxic and quickly hinders root growth, subsequently affecting the absorption of water and nutrients in plants (Agegnehu et al., 2021; Enesi et al., 2023; Rahman et al., 2024).

Relative to the initial pH of 5.07, liming levels of 1.0, 1.5, and 2.0 t ha^{-1} managed to increase the final pH by 0.51, 0.63, and 0.67 units, respectively, during the dry season of 2022. For the rainy season of 2023, the increase in the final pH was 0.75, 0.97, and 1.03 units, with the liming levels of 1.0, 1.5, and 2.0 t ha^{-1} of dolomite, respectively, compared to the initial pH of 5.07 (Figure 2). In the 2023 rainy season, there was a greater increase in final soil pH at all doses evaluated, compared to the 2022 dry season.

The pH increase was 0.24, 0.34, and 0.36 units, for the doses of 1.0, 1.5, and 2.0 t ha^{-1} of dolomite, respectively. The dose of 2.0 t ha^{-1} of dolomite was the one that achieved the greatest increase in pH in both seasons and between planting seasons (Figure 2).

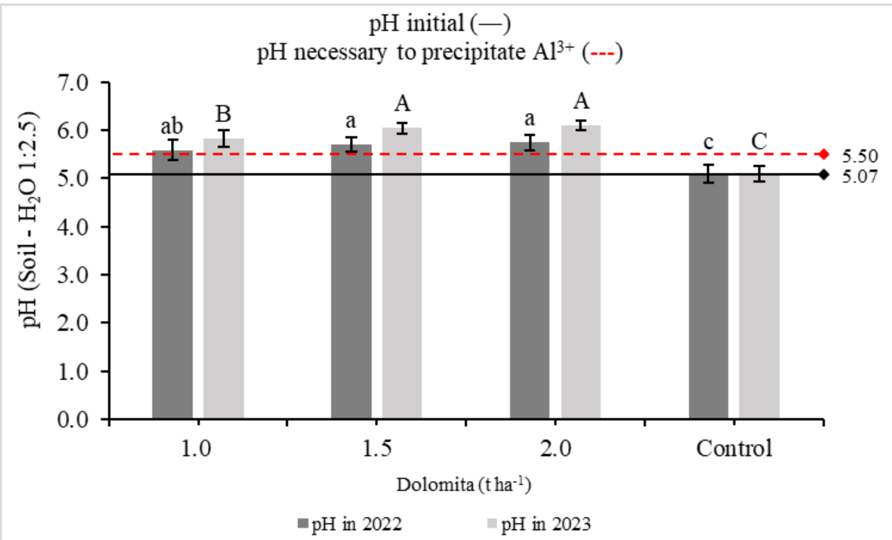

Figure 2. Effect of three levels of dolomite on the pH of an acidic andisol soil. Lowercase letters in dark grey bars and uppercase letters in light grey bars denote significant mean differences for 2022 and 2023, respectively, according to Tukey test (α = 0,05)

The pH results achieved with the evaluated dolomite doses are similar to those reported by Chairiyah et al. (2021), who managed to increase the soil pH up to 5.80 and 6.50 with lime doses of 1.0 and 2.0 t ha^{-1}, respectively, about the initial pH of 4.76. For their part, Agegnehu et al. (2021), indicated that with the application of 1.25 t ha^{-1} of lime, it was possible to increase the pH from 5.03 to 5.64. The results achieved are also close to those described by Dugalić et al. (2023), who reported increases in soil pH up to 6.29 with the application of 1.0 t ha^{-1} of lime. The liming effect promoted a higher concentration of macronutrients in the leaf tissue of corn, in the dry season of 2022 and the rainy season of 2023 (Table 5).

All the evaluated dolomite doses (1.0, 1.5 and 2.0 t ha^{-1}) managed to exceed the critical foliar level of N (2.70%), P (0.20%), K (1.70%), Ca (0.20%), Mg (0.15%) and S (0.10%) established for corn, as described by Correndo & García (2012), with the dose of 2.0 t ha^{-1} of dolomite reaching the highest average values (Table 5).

During the 2023 rainy season, the concentration of macronutrients in corn leaf tissue was increased compared to the 2022 dry season, where the dose of 2.0 t ha-1 stood out with the greatest increase (Table 5). This fact denotes that environmental conditions can influence the effectiveness of liming. In contrast, the control treatment without liming maintained foliar levels of N, K, Ca, Mg, and S below the critical level, except for P, which remained above the aforementioned level, in both planting seasons evaluated (Table 5).

Table 5. The concentration of macronutrients in corn leaf tissue, as a function of dolomite liming levels

Dolomite levels $[CaMg(CO_3)_2]$	Year 2022 (%)						Year 2023 (%)					
	N	**P**	**K**	**Mg**	**Ca**	**S**	**N**	**P**	**K**	**Mg**	**Ca**	**S**
1,0 t ha^{-1}	2,80	0,27	1,93	0,22	0,32	0,19	3,11	0,28	1,98	0,25	0,36	0,22
1,5 t ha^{-1}	2,87	0,29	2,06	0,30	0,48	0,21	3,42	0,32	2,11	0,38	0,51	0,25
2,0 t ha^{-1}	2,96	0,29	2,10	0,34	0,51	0,25	3,51	0,36	2,15	0,41	0,55	0,29
Control	2,58	0,22	1,30	0,12	0,15	0,08	2,61	0,24	1,39	0,13	0,18	0,10
Critical leaf level *	**2,70**	**0,20**	**1,70**	**0,15**	**0,20**	**0,10**	**2,70**	**0,20**	**1,70**	**0,15**	**0,20**	**0,10**

* Critical leaf levels for corn on the cob (Correndo y García, 2012)

These results are close to those described by Crusciol et al. (2019), who recorded an increase in the foliar concentration of N, K, Ca, Mg, and S as the soil pH increased with liming (2.0 t ha^{-1}), except that P did not change due to the effect of liming.

While it is true, the results show that the dose of 2 t ha^{-1} of dolomite lime was the one that achieved the best numerical values to raise the final pH of the soil and achieve a higher concentration of macronutrients in the leaf tissue of corn. However, from an adjustment and optimization point of view, the dose of 1.0 t ha-1 of dolomite could be sufficient to maintain the soil pH above 5.5 and the concentration of macronutrients in the leaf tissue at levels appropriate for corn (Figure 2 and Table 5).

The above highlights the importance of establishing appropriate liming doses to favor the soil environment of the roots to promote the solubilization, availability, and absorption of nutrients, the effect of which is reflected in an adequate concentration of nutrients in the leaf tissue, greater growth and yield (Li et al., 2019; Agegnehu et al., 2021; Enesi et al., 2023).

The increase in growth components (Tables 2 and 3), green and dry matter yield (Table 4), final soil pH (Figure 2), and macronutrient concentration in leaf tissue (Table 5), in the 2023 rainy season, compared to the 2022 dry season, is possibly due to the residual effect of liming in the 2022 season, which added to the effect of liming in 2023, enhanced the neutralizing effect of soil acidity, which, added to environmental conditions such as higher humidity, temperature, and sunlight, could have influenced the greater growth and productivity of corn.

In this context, previous experiences by Crusciol et al. (2019) and Daba et al. (2021) demonstrated that continuous application of liming over several planting cycles led to a significant improvement in soil conditions such as increased pH, cationic bases and reduced Al^{3+} toxicity, which was reflected in the sustained improvement in crop growth and yield.

3.4. Economic component

All liming rates tested improved the economic profitability of corn compared to the control treatment. The economic profitability due to the liming effect of liming was higher than 80% compared to the non-liming treatment, demonstrating the economic viability of this practice on acidic soils (Table 6). However, from the point of view of economic optimization, the 1.5 t ha^{-1} dolomite rate was the one that achieved the highest net economic benefit specific to liming in the 2022 and 2023 planting seasons (Table 6).

Table 6. Economic analysis of liming treatments on forage corn, on an acidic andisol soil

Dolomite levels [$CaMg(CO_3)_2$]	REN Ensilaje	PV	IT = PV*Ren	CT = CF+CV	IN = IT-CT	RBC = IN/CT	Yield (%) = RBC*100	BEN_E = $IN_T - IN_C$
Dry season 2022								
1,0 t ha^{-1}	1119	4	4475	2401	2074	0,86	86	934
1,5 t ha^{-1}	1194	4	4774	2556	2218	0,87	87	1078
2,0 t ha^{-1}	1189	4	4756	2632	2124	0,81	81	984
Control	755	4	3018	1878	1140	0,61	61	-----
Rainy season 2023								
1,0 t ha^{-1}	1182	4	4727	2464	2263	0,92	92	1009
1,5 t ha^{-1}	1252	4	5006	2614	2392	0,92	92	1138
2,0 t ha^{-1}	1228	4	4912	2671	2241	0,84	84	987
Control	792	4	3169	1915	1254	0,65	65	-----

REN = Yield (40 kg bags ha-1); **PV** = Selling price (US$/40 kg bag); **CT** = Total costs (US$ ha-1); **CF** = Fixed costs (US$ ha-1); **CV** = Variable costs (US$ ha-1); **IN** = Net income (US$ ha-1); **RBC** = Benefit-cost ratio; **BENE** = Net economic benefit of liming (US$ ha-1); **INT** = Net income from lime treatments (US$ ha^{-1}); **INC** = Net income from control treatment (US$ ha^{-1})

The profitability and net economic benefit data achieved are close to those reported in Brazil by Crusciol et al. (2019), who obtained a net economic benefit from liming in corn of 746 and 1257 US$ ha^{-1}, in the 2006-2007 and 2007-2008 seasons, respectively. Similarly, Kisić et al. (2021) in Bosnia and Herzegovina, achieved a net gain of between 4005 to 5018 € ha^{-1} due to the effect of liming the soil for corn silage production. For their part, Krismawati et al. (2022) in Indonesia, achieved a net economic income of between 16,510 to 19,580 IDR ha^{-1}, due to the effect of liming acidic soils for corn production.

Finally, the beneficial effect of liming has been widely demonstrated, in improving the chemical fertility of acidic soils, with high concentrations of H^+ and Al^{3+}. When soil is limed, lime dissociates into Ca^{2+}, Mg^{2}+, and OH^- ions. The hydroxyl ion reacts with H^+ and Al^{3+}, generating $Al(OH)_3$ and water, which neutralizes the toxic effect of Al^{3+} and raises soil pH (Li et al., 2019).

The concentration of exchangeable cations such as Ca^{2+}, Mg^{2+}, and K^+, and base saturation are also increased, which improves root growth, facilitating nutrient absorption (Agegnehu et al., 2021; Enesi et al., 2023). Furthermore, the increase in soil pH is related to the presence of basic cations (Ca^{2+}, Mg^{2+}) and anions (CO_3^{-2}) in lime, which can exchange H^+ at the exchange sites, resulting in the formation of H_2O and CO2. Cations occupy the space left by H^+ in the exchange, which contributes to the increase in pH (Li et al., 2019; Enesi et al., 2023).

CONCLUSIONS

All liming doses were effective in increasing the growth, yield, and profitability of forage corn in the study area. The dose of 1.0 t ha^{-1} of dolomite lime was sufficient to improve the growth components of corn. The dose of 2.0 t ha^{-1} of liming was the one that produced the greatest change in the final pH of the soil and led to a greater increase in the concentration of macronutrients in the leaf tissue of corn. From an optimization point of view, the dose of 1.0 t ha^{-1} of lime is sufficient to raise the soil pH above the critical level (5.5) that allows precipitation of Al^{3+} and reduces its toxic effect. In addition, this same dose allows a foliar concentration of macronutrients above the critical level established for corn. The dose of 1.5 t ha^{-1} of dolomite lime was the most appropriate to achieve the highest yields of green and dry matter in forage corn. Furthermore, this dose is the most economically beneficial, making it the recommended dose for the area where the research was conducted.

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CONFLICT OF INTEREST

There is no conflict of interest related to the material in the article.

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