

Behavior of Nitrogen Use Efficiency in Maize (*Zea mays* L.) Under Different Management Conditions in Veracruz, Mexico

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Citation: López-Collado, C. J., Alvarado-Gómez, L. C., Capetillo-Burela, A., Zetina-Lezama, R., Ortega-Jiménez, E., López-Romero, G., Palma-López, D. J., & Reynolds Chávez, M. A. (2025). Behavior of Nitrogen Use Efficiency in Maize (*Zea mays* L.) Under Different Management Conditions in Veracruz, Mexico. *Agro Productividad*. <https://doi.org/10.32854/h6fbkp43>

Academic Editor: Jorge Cadena Iniguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Daniel Alejandro Cadena Zamudio

Received: October 26, 2024.

Accepted: February 14, 2025.

Published on-line: April XX, 2025.

Agro Productividad, 18(3). March. 2025. pp: 229-238.

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ABSTRACT

Currently, technological packages primarily aim to achieve high economic performance without considering environmental impact. This approach promotes the use of agrochemicals, leading to high production costs and negative environmental consequences, while disregarding the efficiency of agro-productive systems.

The objective of this research was to determine dry matter production, nitrogen (N) absorption, and nitrogen use efficiency (NUE) under different maize (*Zea mays* L.) management conditions. The experiment was conducted at the Colegio de Postgraduados, Campus Veracruz.

Using 300-gauge black polyethylene bags, 16 treatments were evaluated, resulting from the combination of the following factors: soil type (crumbly-sandy and loamy), genotype (the hybrid “Orca[®]” seed from Monsanto and the native variety “Olotillo”), nitrogen application (0 and 140 kg N ha⁻¹), and the presence or absence of agricultural lime. A Taguchi L8 orthogonal array was used in a randomized block design with four replications.

For the variables leaf dry weight and root dry weight, significant statistical differences were observed in favor of nitrogen application. The percentage of nitrogen absorption by the plant showed no significant differences for any of the factors or their interactions, whereas nitrogen absorption in grams was higher in fertilized plants. Finally, nitrogen use efficiency (NUE) was higher in unfertilized plants, and the interaction between soil texture and nitrogen concentration was significant.

Keywords: *Zea mays* L., nutritional efficiency, agricultural lime.

INTRODUCTION

Modern crop production is related to the modification and control of management factors that determine higher yields, where the primary criterion favors the combination

of factors that maximize economic performance. However, the efficiency of agro-productive systems is rarely analyzed, particularly in terms of the combination of various management factors.

Considering that agriculture must meet the demand for food and raw materials from a growing population while minimizing environmental contamination risks, sustainable production systems must be implemented to preserve resources for future generations. A key aspect of achieving agroecosystem sustainability is the efficient use of both soil nutrients and applied fertilizers (Salazar *et al.*, 2021).

One of the current challenges in mineral nutrition is the efficiency with which plants utilize nutrients, particularly in the context of the continuously rising cost of fertilizers. Thus, the efficient use of fertilizers applied to crops is one of the most important factors in maintaining food production at a level sufficient to meet population needs, reducing environmental pollution and production costs, while increasing agricultural profitability.

Fageria *et al.* (2011) state that nutrient efficiency in crops refers to the ability to produce a greater amount of dry biomass per unit of applied or absorbed mineral. Differences in crop yield are attributed both to the efficiency of nutrient acquisition by the roots and to the plant's effective utilization of these nutrients.

Regarding nutrient use efficiency, the following findings have been reported: 1) It is a plant adaptation mechanism to low-fertility conditions (Retuerto & Woodward, 2003); 2) In maize varieties and hybrids, differences in yield and efficiency have been observed (Delgado, 2002); 3) Higher-yielding plants are not always the most efficient (Sosa & García, 2018); and, 4) In maize, nitrogen use efficiency varies from 44% to 143% (González *et al.*, 2014).

Gallais and Hirel (2004) and Xu *et al.* (2012) suggest that through a combination of management practices, technologies, and genetic improvement, efficiencies above 85% can be achieved. Furthermore, each improvement in nitrogen use efficiency (NUE) reduces nitrogen losses, and by increasing its absorption, it proportionally enhances economic returns, particularly under high fertilizer cost conditions.

Nitrogen is an essential element for photosynthesis. In other words, for plants to fix carbon from the air, accumulate dry matter, and achieve economically attractive yields, a sufficient supply of this element is required. However, nitrogen is often a limiting nutrient in agricultural soils (Delgado, 2002; Zenteno *et al.*, 2019).

Nitrogen use efficiency (NUE) depends on several factors, including soil pH, soil type, crop species, agroecosystem type, type of fertilizer applied, and management practices (Smith, 2020).

The Taguchi experimental design is a factorial arrangement used in exploratory studies. It offers advantages such as reducing the number of treatments, experimental units, and overall experiment costs. This design is based on the confounding of effects, which results in a loss of precision when analyzing high-order interactions. However, these interactions are generally of low importance and difficult to interpret. This loss is compensated by an increase in the precision of the main effects (Padrón, 1996).

Each variety within the same species can also exhibit particular characteristics of behavior and production, reflected in different capacities for nutrient absorption and

utilization. Therefore, it is important to evaluate different maize genotypes in order to identify efficient materials and incorporate them into agroproductive systems, which will bring economic benefits to producers and ecological benefits due to better fertilizer use (Bertsch, 2005; Herrera *et al.*, 2022).

Finally, understanding the physiological and genetic foundations of nitrogen use efficiency is necessary. Thus, the objective of this research was to evaluate dry matter production, nitrogen absorption, and nitrogen use efficiency (NUE) in maize under different management conditions, based on the hypothesis that management factors modify these variables.

MATERIALS AND METHODS

Study Area

The experiment was conducted in 300-gauge black bags from February 24 to April 7, 2007, on the grounds of the Colegio de Postgraduados, Veracruz Campus, in the “Tepetates” property, located in the municipality of Manlio Fabio Altamirano, at coordinates 19° 16’ North Latitude and 96° 16’ West Longitude, at an altitude of 40 m (García, 2004).

Treatments and Experimental Design

Sixteen treatments were evaluated, resulting from the combination of the following factors: soil texture (crumb-sandy and loamy), genotype (hybrid seed “Orca[®]” from Monsanto and the native variety “Olotillo”), nitrogen (0 and 140 kg N ha⁻¹), and with or without agricultural lime. The factors under study and their levels are presented in Table 1.

A Taguchi L 8⁻¹ orthogonal arrangement (Stuart, 1993) was used in a randomized block experimental design with 16 treatments and four replications per treatment. The assignment of 300-gauge polyethylene black bags in the field was done randomly, with each bag representing an experimental unit placed randomly. A light variation gradient was identified based on the sun’s path, so the randomized blocks were positioned perpendicular to this gradient.

Soil Characteristics Under Study

Soil from two maize-producing regions in the municipality of Acayucan, Veracruz, was used: La Colonia Hidalgo (Soil A) and La Colonia Agrícola Michapan (Soil B). The soil analyses were carried out at the Soil Laboratory of the Colegio de Postgraduados Veracruz Campus, and their physical and chemical characteristics are presented in Table 2.

Table 1. Factors and Levels Under Study.

Factors	Level 1	Level 2
Type of soil	Sandy loam (S1)	Loam (S2)
Genotype	Olotillo (G1)	Orca (G2)
Nitrogen	0 kg ha ⁻¹ (N1)	140 kg ha ⁻¹ (N2)
Lime	Without agricultural lime (C1)	With agricultural lime (C2)

Table 2. Physical and Chemical Characteristics of the Soils used in the Study.

Characteristic	Soil A	Soil B
Texture	Sandy loam	Loam
Sand	76.7%	41.8%
Silt	7.0%	31.8%
Clay	16.3%	26.4%
pH-H ₂ O	4.7	5.5
Organic matter	2.3% (medium)	2.9% (medium)
Total nitrogen	0.11% (medium)	0.14% (medium)
Phosphorus	1 ppm (very low)	4 ppm (low)
Potassium	50 ppm (low)	100 ppm (medium)
Calcium	960 ppm (low)	2,160 ppm (moderately high)
Magnesium	37 ppm (medium)	487 ppm (very high)

Sowing

Sowing was carried out in black polyethylene nursery bags, measuring 30 cm × 40 cm in width and length, respectively. In each black bag containing the corresponding soil type, three seeds were placed at the center of the bag, at a depth of 3 cm. Once germinated, one plant per bag was selected, and the others were removed. The bags were arranged so that the distances between plants and rows were 20 cm and 40 cm, respectively.

Fertilization

The fertilization formula applied was equivalent to 140-60-60 kilograms of nitrogen (N), phosphorus (P₂O₅), and potassium (K₂O) per hectare, respectively. The dose was split into two parts: all of the P and K, along with half of the N, were applied at planting, and the other half of the N was applied 20 days after sowing (das). The sources used were urea, triple superphosphate, and potassium chloride.

Lime Application

Titration tests with sodium hydroxide (NaOH) were performed in the laboratory to determine the lime requirements and adjust the pH of the soils used, from 4.7 and 5.5 to 7.0, following the methodology described by Ortega (1981). For liming the experimental units, dolomitic lime with a purity of 78% was used, at doses of 2.7 t ha⁻¹ and 0.9 t ha⁻¹ for the crumb-sandy and loamy soils, respectively, and was applied at planting.

Irrigation

Light and frequent irrigations were scheduled according to the water requirements of the treatments, applied using a watering can. The field capacity (FC) and the permanent wilting point (PWP) of each soil were considered, and both FC and PWP were calculated using the gravimetric method. Soil moisture was maintained within a range of 60 to 75% of available moisture.

Sample Handling

Based on a study by Delgado (2002) and Yato *et al.* (2015), which found a significant correlation ($P \leq 0.01$) ($r = 0.92$) between the kilograms of dry matter (DM) and the kilograms of nitrogen absorbed per hectare at 30 days after planting, the decision was made to collect samples at 35 days after sowing (dds). Pruning shears were used to cut the above-ground parts of the maize plants (leaves and stems) into fractions, and these were placed in pre-labeled paper bags with the corresponding treatment and replication numbers. The roots were collected and any soil fractions were removed using running water with a hose. These were also placed in labeled paper bags. All samples were then dried in a forced-air oven at a temperature of 60 °C until a constant weight was achieved.

Chemical Analysis of Samples

The analysis of the leaf and stem samples was carried out at the High Technology Laboratory of Orizaba S. C. (LATO). The methods and procedures used were as follows: dry weight of leaves and stems was determined by gravimetry, and nitrogen (N) was measured using the Kjeldahl method. Additional analyses for other elements were conducted; for this, the samples were first incinerated at 550 °C, and the dissolution of the ash allowed for the determination of calcium (Ca), magnesium (Mg), and potassium (K) through atomic absorption. Phosphorus (P) was determined by UV-VIS spectrophotometry.

Registered Variables

The dry weight of leaves and stems (DWLaS) and roots (DWR) were determined using a granatary balance. The dry weight of leaves and stems in kg DM/ha and nitrogen absorption in kg N/ha were obtained through data transformation, considering a population density of 62,500 plants per hectare. Nitrogen absorption in percentage was calculated from laboratory results, and nitrogen absorption in grams per plant was determined based on the dry weight of each plant. The nitrogen use efficiency (NUE) was defined by the following mathematical formula:

$$NUE = \text{dry weight of leaves and stems (DWLaS) in grams} / \text{grams of N absorbed}$$

Statistical analysis

For the studied variables, analysis of variance and mean comparison tests were conducted using the Tukey method, $p \leq 0.05$, with the Statistica software. Interactions that were statistically significant were graphed and interpreted (Gómez and Gómez, 1983). For the variable nitrogen absorption as a percentage, a square root transformation was applied to the original data.

RESULTS AND DISCUSSION

Dry weight of leaves and stems (DWLaS)

The analysis of variance for the dry weight of leaves and stems (DWLaS) revealed a statistical difference ($p \leq 0.01$) only for the nitrogen factor, which was confounded with the interaction of soil \times genotype \times lime (Table 3). To determine which of these two

Table 3. Analysis of variance for the variables dry weight of leaves and stems (DWLaS) and dry weight of roots (DWR).

FV	DF	SM (PSHyT)	SM (PSR)
Blocks = soils × genotypes × N × lime	3	125.37*	56.93
Soils = genotype × nitrogen × lime	1	0.34	14.44
Genotypes = soils × nitrogen × lime	1	43.89	2.25
Nitrogen = soils × genotypes × lime	1	933.12**	283.81**
Soils × genotypes = nitrogen × limel	1	7.84	0.05
Soils × nitrogen = genotypes × lime	1	2.88	2.36
Genotypes × N = soils × lime	1	0.91	87.44
Soils × genotypes × nitrogen = limel	1	69.08	60.77
Error	21	650.41	41.35
Total	31	2084.64	1490.40

*** Tukey's significance levels at $p \leq 0.05$ (*) and $p \leq 0.01$ (**) probability levels, respectively.

effects showed statistical significance, the mean comparison for nitrogen (Table 4) was examined, showing values of 14.35 and 25.15 grams per plant for the 0 and 140 kg of nitrogen per ha doses, respectively. This difference provides sufficient evidence to favor nitrogen application. When the DWLaS values were transformed to kg DM/ha for the 0 and 140 kg N/ha doses (Table 4), the observed values were 807.2 and 1414.7, respectively. These values closely match those obtained by Delgado *et al.* (2004) for maize in Venezuela, with 806 and 1469 kg DM/ha for the 0 and 120 kg N/ha doses, respectively, 30 days after planting. Delgado (2002) and Naiz *et al.* (2015) indicate that the crop growth rate increases with higher nitrogen doses. Moreover, dry matter production is closely related to the amount of nitrogen absorbed, which in turn depends on the available nitrogen. The evidence of higher photosynthesis rates under higher nitrogen absorption conditions could explain the greater dry matter production in the treatments with higher nitrogen doses compared to the unfertilized treatments.

Table 4. Mean comparison for the variables dry weight of leaves and stems (DWLaS) and dry weight of roots (DWR).

Factors	Dry weight of leaves and stem (g planta ⁻¹)	Dry weight of leaves and stem (kg MS ha ⁻¹)	Dry weight of roots (g planta ⁻¹)
Creole variety	19.65a ¹	1105.3a	18.20a ¹
Hybrid	19.86a	1117.1a	16.85a
Sandy loam soil	18.58a	1045.1a	17.79a
Loam soil	20.92a	1176.7a	17.26a
Without nitrogen	14.35b	807.2b	14.55b
With nitrogen	25.15a	1414.7a	20.50a
Without agricultural lime	19.21a	1080.6a	17.23a
With agricultural lime	21.13a	1188.6a	18.05a

¹ Means with the same letters within factors indicate no statistical difference between the levels (Tukey, 0.05).

Dry Weight of Roots (PSR)

Regarding the variable dry weight of roots (Cuadro 3), a highly significant difference ($p \leq 0.01$) was found for the nitrogen factor, with values of 14.35 and 25.15 g for the doses of 0 and 140 kg N ha⁻¹, respectively (Cuadro 4).

Nitrogen absorption percentage (%)

The analysis of variance for the variable nitrogen absorption percentage did not show statistical differences for any of the factors or their interactions (Table 5). That is, regardless of the plant size, the nitrogen content percentage remained constant.

Nitrogen Use Efficiency (NUE)

For NUE, statistical differences were found for the nitrogen factor ($p \leq 0.01$) and for the nitrogen \times soil interaction ($p \leq 0.05$), as indicated in Table 5. The means for NUE were 72.0 and 53.3 g DM per g of N absorbed for the 0 and 140 kg N/ha doses (Table 6). These values fall within the ranges reported by Delgado (2002), which are from 60 to 90 g DM per kg of N absorbed at 90 days after planting. When comparing NUE in soils without and with nitrogen application, an inverse relationship was found between NUE and the N dose applied, meaning that NUE was higher in the treatment where no nitrogen was applied. This can be explained by the fact that under stress conditions, plants have compensatory functions, and the increase in physiological efficiency is a mechanism of adaptation to low fertility conditions (Shi *et al.*, 2001).

Nitrogen absorption (g plant⁻¹)

The analysis of variance for the variable nitrogen absorption (g plant⁻¹) only showed a statistical difference for the nitrogen factor, with values of 0.25 g and 0.50 g for the levels of

Table 5. Analysis of variance for the variables: nitrogen absorption (%), nitrogen absorption (grams), and nitrogen use efficiency (NUE).

FV	DF	MS Absorption of N (%)	MS Absorption of N (g)	MS NUE (kg MS kg N absorbido ⁻¹)
Blocks = soils \times genotypes \times N \times lime	3	0.37	0.09*	643.96
Soils = genotypes \times nitrogen \times lime	1	0.08	0.004	362.67
Genotypes = soils \times nitrogen \times lime	1	0.002	0.01	25.25
Nitrogen = soils \times genotypes \times lime	1	1.15	0.5**	2554.25**
Soils \times genotypes = nitrogen \times lime	1	0.37	0.03	235.07
Soils \times nitrogen = genotypes \times lime	1	1.12	0.03	1685.93*
Genotypes \times N = soils \times lime	1	0.17	0.009	274.67
Soils \times genotypes \times Nitrogen = lime	1	0.007	0.042	28.26
Error	21	6.43	0.43	9251.77
Total	31	10.48	1.34	16340.40

* ** Significant at Tukey levels $p \leq 0.05$ and $p \leq 0.01$ probability, respectively. Square root transformation was applied to the original data.

Table 6. Comparison of means for the variables: nitrogen absorption percentage, nitrogen absorption in grams, and nitrogen use efficiency (NUE).

Factors	Absorption of N (%) [†]	Absorption of N (g/plant)	Absorption of N (kg N/ha)	NUE (kg DM/kg N absorbed)
Creole variety	1.85 a	0.38 a	21.4 a	59.6 a ¹
Hbrid	1.74 a	0.36 a	20.2 a	65.7 a
Sandy soil	1.79 a	0.35 a	19.7 a	63.8 a
Clayed soil	1.80 a	0.39 a	30.0 a	61.5 a
Without nitrogen	1.60 a	0.25 b	14.1 b	72.0 a
With nitrogen	1.90 a	0.50 a	28.1 a	53.3 b
Without agricultural lime	1.65 a	0.35 a	19.7 a	63.3 a
With agricultural lime	1.68 a	0.40 a	22.5 a	65.7 a

¹ Means with the same letters within factors indicate no statistical difference between the levels (Tukey, 0.05).

[†] The square root transformation was applied to the original data.

0 and 140 kg N ha⁻¹, respectively (Table 6). This is due to the close relationship between absorbed N and available N in the soil, which has been documented by Ding *et al.* (2005), who indicate a linear relationship between both variables.

Nitrogen Use Efficiency (NUE)

For NUE, statistical differences were found for the nitrogen factor ($p \leq 0.01$) and for the soil by nitrogen interaction ($p \leq 0.05$), as indicated in Table 5. The means for NUE were 72.0 and 53.3 g DM g N absorbed¹ for the 0 and 140 kg N/ha doses, respectively (Table 6). These values fall within the ranges reported by Delgado (2002), from 60 to 90 kg of DM per kg of N absorbed at 90 days after planting. When comparing NUE in soils with and without nitrogen application, an inverse relationship was found between NUE and the nitrogen dose applied, *i.e.*, NUE was higher in the treatment where no nitrogen was applied. This can be explained by considering that, under stress conditions, plants exhibit compensatory functions. Furthermore, an increase in physiological efficiency is a mechanism by which plants adapt to low fertility conditions (Shi *et al.*, 2001).

Soil Texture by Nitrogen Interaction

Since the first-order interactions of soil \times nitrogen and genotypes \times lime were confounded (Table 5), and given that a statistical difference was observed as a main effect for the nitrogen factor, it was considered that the significant interaction is the one involving nitrogen. Therefore, the significant interaction was determined to be soil texture \times nitrogen. The highest NUE was obtained in treatments where no nitrogen was applied, especially in the sandy-loam soil. These differences are attributed to both the efficiency of nutrient acquisition by the roots and the proper utilization of nitrogen by the plant, confirming that plants under stress conditions develop compensatory mechanisms that increase efficiency in physiological processes, in this case, nitrogen use efficiency in low-fertility soils (Retuerto and Woodward, 2003).

CONCLUSIONS

For the variables dry weight of leaves and dry weight of roots, only statistically significant differences were observed in favor of nitrogen application. Nitrogen absorption percentage showed no differences for any of the factors studied, nor their interactions, while nitrogen absorption in grams was higher in fertilized plants. Nitrogen use efficiency was higher in unfertilized plants due to the homeostatic adaptation mechanism present in all species. The soil \times nitrogen interaction was statistically significant due to the deficient nature of the soil and the absorption capacity of the plants.

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