AGRO PRODUCTIVIDAD

Colegio de
Postgraduados

Chemical Edaphic Gradients in Traditional Native Maize (*Zea mays* L.) Production Systems in the Lower Chinantla

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Citation: Ruíz-Luna, J., Santiago-López, U., Martínez-Martínez, R., Velasco-Velasco, V. A., Andrio-Enríquez, E., & Vásquez-Procopio, J. (2026). Chemical Edaphic Gradients in Traditional Native Maize (*Zea mays* L.) Production Systems in the Lower Chinantla. *Agro Productividad*. https://doi.org/10.32854/yz5qpy76

Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Juan Francisco Aguirre Medina

Received: December 20, 2025.
Accepted: March 19, 2026.
Published on-line: May XX, 2026.

Agro Productividad, 19(5). May. 2026. pp: 147-156.

ABSTRACT

Objective: Soil chemical properties directly influence soil fertility and can be modified by management practices, particularly in traditional agricultural systems. This study aimed to determine soil chemical properties and identify edaphic gradients in native maize production systems in the Lower Chinantla region of Oaxaca, Mexico.

Design/Methodology/Approach: Thirty-two soil samples were collected through participatory random sampling with producers of native Tuxpeño maize in June 2025. Soil pH, electrical conductivity, organic matter, and the concentrations of P, K, Ca, Mg, Fe, Mn, Zn, and Cu were determined in accordance with NOM-021-RECNAT-2000 guidelines. Variability in soil chemical properties was evaluated using descriptive statistics, and edaphic gradients were identified through principal component and cluster analyses.

Results: High variability was observed in organic matter, P, and Fe. Two main edaphic gradients were identified: one associated with soil fertility and another related to exchangeable bases, with Ca as the dominant variable.

Study Limitations/Implications: Limitations include the absence of control over climatic, topographic, and vegetation cover variables. In addition, the form, source, and application rate of fertilizers used in previous cropping cycles may have influenced soil heterogeneity.

Findings/Conclusions: The results underscore the importance of considering edaphic gradients in the management of traditional agricultural systems as a strategy to optimize soil fertility and enhance native maize productivity.

Keywords: Multivariate analysis; soil fertility; traditional agricultural systems

INTRODUCTION

Soil constitutes an essential matrix in agricultural systems. Nutrient availability, vegetative growth, and ecosystem sustainability depend on the condition of its physical, chemical, and microbiological properties. Soil pH, electrical conductivity (EC), organic matter (OM),

cation exchange capacity, and the concentration of chemical elements are fundamental chemical and physicochemical properties whose values are associated with geographic region, agricultural practices, land use, and the presence of environmental factors (Patra *et al.*, 2024).

In tropical regions, processes such as weathering, soil formation, leaching, and agricultural management are associated with edaphic heterogeneity, thereby indicating variation in soil chemical composition (Martínez-Trinidad *et al.*, 2008; Sánchez Bernal *et al.*, 2012). In this context, one way to describe soil variability and fertility conditions is to examine each variable individually through descriptive statistics; however, this approach is limited when the objective is to explain how a group of edaphic variables interact jointly.

For this purpose, multivariate analyses, particularly principal component analysis (PCA) and cluster analysis, are highly relevant and have been used to integrate multiple variables and identify edaphic gradients associated with fertility processes, base balance, and nutrient dynamics in agricultural soils, including tropical soils (Quispe *et al.*, 2021; Silva *et al.*, 2019). Mexico is the center of origin and diversification of maize (*Zea mays* L.), with 59 native races that symbolize the country's roots, identity, and biocultural heritage (Castro *et al.*, 2013; Suárez *et al.*, 2013). This racial diversity derives from agricultural practices developed over thousands of years, rooted in the knowledge and customs of Indigenous peoples, in which soil management is largely based on traditional practices, thereby giving rise to diverse edaphic gradients (Josset *et al.*, 2015; Sampaio, 2008). In some communities of the Chinantla region of Oaxaca, native maize cultivation continues to rely on traditional agricultural practices, such as the milpa system, crop rotation, direct sowing without conventional tillage, and reduced use of agrochemicals. In this regard, although studies have evaluated soil chemical properties and described edaphic gradients in tropical agricultural systems and native maize production systems, a local-scale information gap persists, particularly in southeastern Mexico, regarding the influence of these traditional practices on the variability of soil chemical properties and on the configuration of functional edaphic gradients (Bautista & Aguilera, 2023; Nuñez-Peñaloza *et al.*, 2023).

This issue is especially relevant because the conservation and production of native maize under sustainable management across various regions of Mexico have now become a crucial public policy priority for achieving food sovereignty, as established in the National Native Maize Plan presented by the Government of Mexico in November 2025.

Therefore, the variability of soil chemical properties was analyzed and the main edaphic gradients were identified in native maize production systems in two communities of the Lower Chinantla, Oaxaca, in order to contribute to the understanding of edaphic heterogeneity and generate information that may optimize soil management and improve agricultural productivity in traditional systems.

MATERIALS AND METHODS

Study site

A social intervention was conducted with n=32 producers of native Tuxpeño maize, who voluntarily provided soil samples from their agricultural plots. From each plot of approximately half a hectare, a composite sample of 2 kg of soil was prepared from ten subsamples collected at a depth of 0-20 cm. Of the participating producers, 23 were from the community of San José Mano Marqués, municipality of San Juan Bautista Ayotzintepec, and nine were from San Agustín, municipality of Santa María Jacatepec. Both communities are located in the Lower Chinantla region, which, due to its high temperatures, abundant rainfall, and elevated humidity, is considered a tropical zone of the state of Oaxaca.

Soil analysis

The soil samples were prepared for laboratory analysis in accordance with the Official Mexican Standard (NOM-021-RECNAT-2000). The chemical variables determined were pH, EC, OM, and the concentrations of the chemical elements P, K, Ca, Mg, Fe, Mn, Zn, and Cu.

Statistical analysis

The data were analyzed in R, version 4.5.1. descriptive statistics used to evaluate the distribution and variability of soil chemical properties included mean, median, standard deviation, minimum value, and maximum value. In order to integrate the data from all variables and analyze the relationships among them, PCA was performed using the FactoMineR and Factoextra packages, based on a correlation matrix. The principal components were selected according to the percentage of explained variance and the edaphic interpretation of the variables associated with each component. In addition, a cluster analysis was carried out to identify groups of samples with similar characteristics among plots. The distance between samples was calculated using Euclidean distance and Ward's clustering method through base R functions.

RESULTS AND DISCUSSION

Diversity of soil chemical properties

According to the chemical analysis of the soils from the studied tropical region, the results are presented in full in the supplementary Excel file (Table S1). Soil pH ranged within a narrow interval of 5.1-6.5 (Figure 1), indicating moderately acidic soils. OM showed high variability among sampling sites: ten soils exhibited low contents (0.6-0.8%), 17 showed intermediate values (1.6-3.5%), and five soils presented high values ($>$3.6%).

This high variability may be attributed to differences in management practices, the persistence of plant residues such as stubble and their contribution of biomass, agricultural intensification, and microenvironmental conditions among plots (Armida-Alcudia *et al.*, 2005; Cristóbal-Acevedo *et al.*, 2008; Martínez-Trinidad *et al.*, 2008). In cases where OM increased, this may be related to soil acidity, since OM decomposition releases H^+ and produces organic acids; moreover, the CO_2 released by microorganisms may react with water and form weak acids, such as carbonic acid (Macias *et al.*, 2020; Malik *et al.*, 2018).

Likewise, it has been reported that acidic soils in tropical environments are associated with processes of weathering, pedogenesis, and leaching (Quintero Ramírez *et al.*, 2017). EC showed a narrow range of values, all below 1 dS m^{-1} (Figure 1), which confirms the absence of salinization processes and suggests that agricultural management practices are the factors responsible for the observed variability in nutrients rather than salt

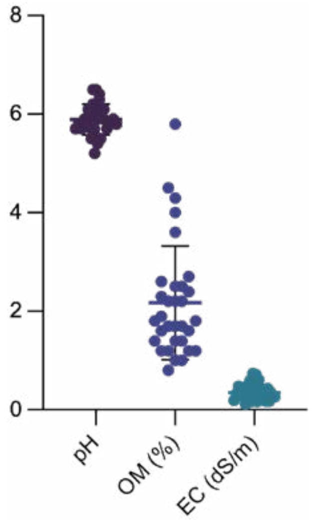

Figure 1. Soil pH, organic matter (OM), and electrical conductivity (EC) values in Chinantec producers of native maize. Each point represents the individual values of the samples. Standard deviation and mean are indicated in the panels. n=32.

accumulation. This behavior is consistent with reports from rainfed systems in regions with high precipitation, where leaching prevents nutrients from accumulating in the soil (Rodríguez *et al.*, 2006).

The primary nutrients K and P showed a wide distribution across the sampling sites (Table S1, Figure 2). In particular, P predominantly exhibited low concentrations (<15 mg kg^{-1}), whereas three sites showed intermediate values (15-30 mg kg^{-1}) and two sites presented high concentrations (>30 mg kg^{-1}).

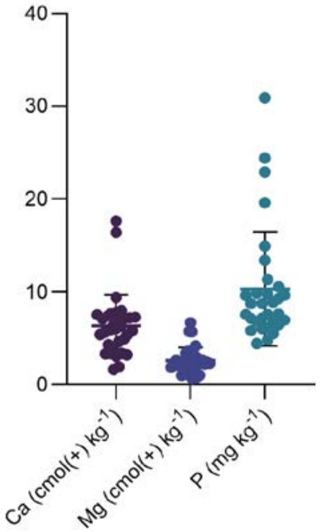

Figure 2. Calcium, magnesium, and phosphorus concentrations in soil samples from Chinantec producers of native maize. Each point represents the individual values of the samples. Standard deviation and mean are indicated in the panels. n=32.

This variability is consistent with the fact that P is a highly dynamic chemical element derived from weathering, and its availability in cropping systems depends on the appropriate use of fertilizers (Novelo *et al.*, 2000). In the case of K, most samples were concentrated within very low (<0.2 mg kg^{-1}) to low (0.2-0.3 mg kg^{-1}) values. The secondary nutrients Mg and Ca also exhibited marked variability. With respect to Ca, 11 soils showed low concentrations (<5 cmol$^{(+)}$ kg^{-1}), 19 presented intermediate values (5-10 cmol$^{(+)}$ kg^{-1}), and two exhibited high concentrations (>10 cmol$^{(+)}$ kg^{-1}). For Mg, most samples fell within intermediate concentrations (1.3-3.0 cmol$^{(+)}$ kg^{-1}), with some high values (>3.0 cmol$^{(+)}$ kg^{-1}). The dispersion observed in K, as well as in Ca and Mg, suggests differences in the balance of exchangeable bases and, similarly, their association with leaching processes, thereby reflecting distinct edaphic conditions among plots (Martínez *et al.*, 2020).

Regarding the micronutrients Fe, Cu, and Zn, Fe exhibited the greatest variability, with extreme values at certain sites (Figure 3). This pattern may be attributed to weathering processes in the study sites or to soil redox reactions influenced by OM and pH (Acevedo *et al.*, 2004). Taken together, these results confirm that traditionally managed agricultural systems exhibit clear edaphic heterogeneity at the local scale (Vásquez Agustín *et al.*, 2009).

Identification of edaphic gradients

Based on the variability observed in soil chemical properties, a principal component analysis (PCA) was performed to integrate the information, analyze the relationships among variables, and investigate the presence of edaphic gradients. The first two components jointly explained 49.7% of the total variability, with the first component accounting for 31.1% and the second for 18.6% (Figure 4).

PC1 showed positive correlations with OM (0.77), K (0.72), Mn (0.89), Fe (0.50), and EC (0.74) (Table 1), suggesting a soil chemical fertility gradient that integrates processes associated with the input and decomposition of organic residues, nutrient availability, and cation retention.

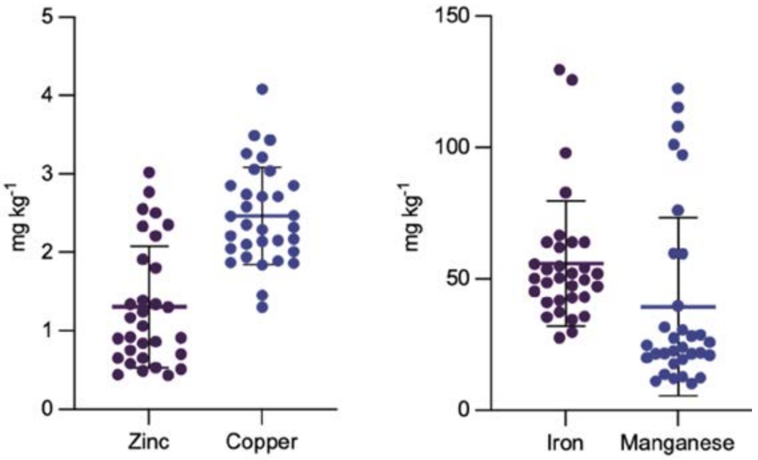

Figure 3. Concentration of the micronutrients zinc, copper, iron, and manganese in soil samples from Chinantec producers of native maize. Each point represents the individual values of the samples. Standard deviation and mean are indicated in the panels. n=32.

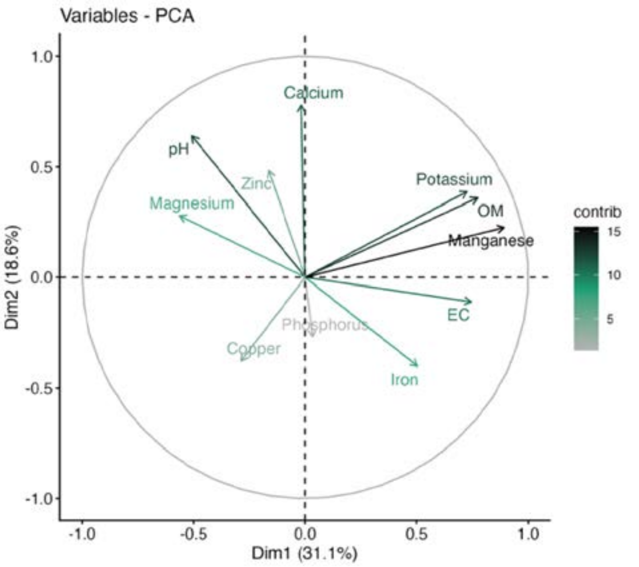

Figure 4. Correlation circle from the principal component analysis of soil chemical properties. The length and direction of the arrows indicate the contribution and correlation of the variables with the first two principal components (Dim1 and Dim2).

Table 1. Correlation coefficients of each original variable with the identified principal components (Dim).

Variable	Dim. 1	Dim. 2	Dim. 3	Dim. 4	Dim. 5
pH	−0.507	0.640	−0.108	0.356	0.069
CE	0.745	−0.111	−0.244	0.269	−0.287
MO	0.773	0.359	0.180	−0.177	0.325
P	0.033	−0.269	0.784	0.127	−0.306
Ca	−0.018	0.778	−0.118	0.441	−0.001
Mg	−0.564	0.278	0.399	−0.062	0.509
K	0.726	0.387	0.216	0.122	−0.081
Fe	0.503	−0.402	0.395	0.294	0.474
Mn	0.892	0.225	−0.068	0.075	0.050
Zn	−0.162	0.482	0.583	−0.120	−0.429
Cu	−0.287	−0.378	0.056	0.829	−0.004

This is consistent with findings reported in studies of tropical agricultural soils, where OM acts as the central axis in structuring soil fertility (Armida-Alcudia *et al.*, 2005; Nuñez-Peñaloza *et al.*, 2023). In contrast, negative PC1 values were associated with pH (−0.50) and Mg (−0.56), indicating the presence of contrasting edaphic conditions within the same management system.

PC2 was dominated by Ca, which showed a high contribution and a positive correlation (0.77) with this component, whereas P exhibited a lower contribution (−0.26) and was located near the origin of the coordinate system (Figure 4).

The role of Ca in this component reflects an independent gradient associated with the balance of exchangeable bases in the soil. This pattern is consistent with that reported by

Armida-Alcudia *et al.* (2005), who observed that differences in base saturation and leaching processes generate secondary axes of edaphic variation in tropical soils. The smaller contribution of PC2 to the total variability suggests that, although exchangeable bases influence soil chemical properties, their effect is less pronounced than that of the fertility gradient identified by PC1.

Taken together, these results demonstrate that soil chemical properties do not vary independently, but rather as the outcome of interconnected edaphic processes (Quispe *et al.*, 2021), and they underscore the usefulness of multivariate analyses for identifying functional edaphic gradients in native maize production systems at the local scale.

Soil distribution and grouping in space

To analyze the functionality of the edaphic gradients identified in the PCA (Figure 4) and evaluate soil distribution, a cluster analysis was performed (Figure 5). This analysis revealed two clearly distinct groups, which were separated along the horizontal axis of PC1 and overlapped along the vertical axis of PC2. The formation of these two groups confirms that the chemical fertility gradient is the main axis defining variability among the studied plots, as has been documented in studies of tropical agricultural soils (Armida-Alcudia *et al.*, 2005).

With respect to the soils concentrated in Group 2, most corresponded to positive PC1 values and exhibited greater contributions and contents of OM, K, Mn, and EC. In contrast, the samples in Group 1 were primarily associated with negative PC1 values and were related to pH, Mg, Zn, and Cu, suggesting edaphic conditions of lower fertility, while simultaneously indicating the existence of soils with distinct chemical characteristics within the same traditional production system and study area. Moreover, PC2 contributed to a lesser extent to the differentiation between the two groups and was more strongly

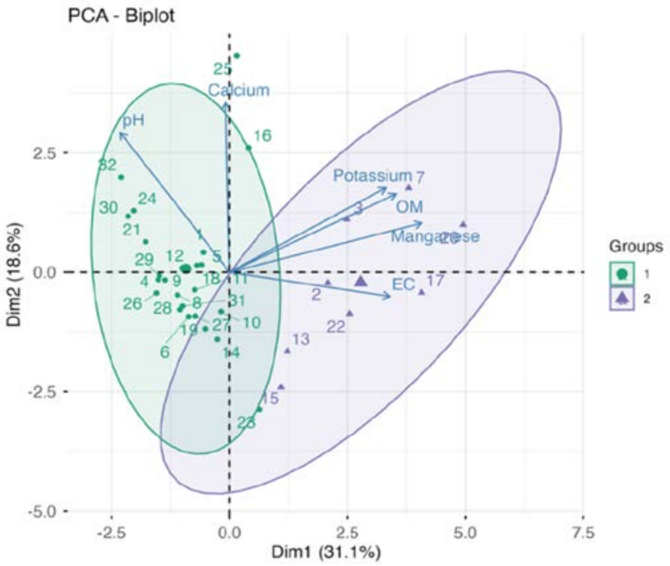

Figure 5. Distribution of soils in multivariate space and their grouping by cluster analysis. The ellipses represent groups defined by the cluster analysis. The arrows indicate the chemical variables.

influenced by Ca, which suggests a reduced capacity to distinguish among soils compared with the fertility gradient represented by PC1. The relationship between the PCA structure and the groups obtained through cluster analysis indicates the robustness of the multivariate techniques employed to identify and differentiate edaphic gradients (Barrezueta Unda *et al.*, 2017; Parra *et al.*, 2017). In the context of native maize production systems in the Lower Chinantla, Oaxaca, the grouping of producers' plots (Figure 5) reveals the presence of edaphic mosaics shaped by the interaction between soil chemical properties and traditional agricultural practices. These patterns reflect marked edaphic heterogeneity at the local scale, consistent with findings reported for agricultural systems in rural communities, where environmental and cultural diversity is associated with high soil heterogeneity (Sampaio, 2008; Uzcanga Pérez *et al.*, 2020). Unlike previous studies conducted in tropical regions, this work provides empirical evidence of chemically dynamic soils within a single traditional production system, thereby broadening the understanding of edaphic heterogeneity in native maize cultivation and providing a scientific basis for guiding more specific and sustainable soil management strategies for producers in the Chinantla region. Despite the contributions of this research, several methodological limitations should be acknowledged. For instance, the analysis focused exclusively on soil chemical properties without incorporating physical and microbiological variables, which also influence the configuration of edaphic gradients, as well as climatic, topographic, and vegetation cover variables. Likewise, no control or record was kept of the form, source, and rate of fertilization used in previous cropping cycles. In addition, the study was conducted with producers from only two communities, which limits the extrapolation of the results to other sites in the region. Nevertheless, these limitations open valuable opportunities for future research encompassing a broader range of variables and scales of analysis.

CONCLUSIONS

The chemical variables OM, K, P, and Fe showed high variability, whereas pH and EC exhibited smaller changes, suggesting relatively homogeneous edaphic conditions in terms of acidity and salinity. PCA enabled the identification of two edaphic gradients: the first was characterized by higher OM and nutrient contents associated with soil fertility; the second was related to exchangeable bases, with Ca standing out as the dominant variable. The distribution of soils in multivariate space and their grouping reflect the expression of these edaphic gradients, thereby evidencing soil chemical heterogeneity among plots and confirming the usefulness of multivariate analyses for integrating and synthesizing information from diverse edaphic variables. Finally, this study highlights the importance of considering agricultural management approaches as a strategy to optimize soil fertility and contribute to increased native maize production in the communities of the Lower Chinantla, Oaxaca.

ACKNOWLEDGMENTS

This research is part of project PEE-2025-G-602, entitled "Nutritional Quality of Maize Races (*Zea mays* L.) of Biocultural Importance in the Chinantla Region, Oaxaca, Mexico," funded by the Ministry of Science, Humanities, Technology, and Innovation (SECIHTI).

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