Article

Adaptation of agricultural practices for the sustainability of sugarcane production in the Northern Huasteca Region in Response to Climate Change

Adaptación de prácticas agrícolas para la sostenibilidad de la producción de caña de azúcar en la Región Huasteca Norte frente al Cambio Climático

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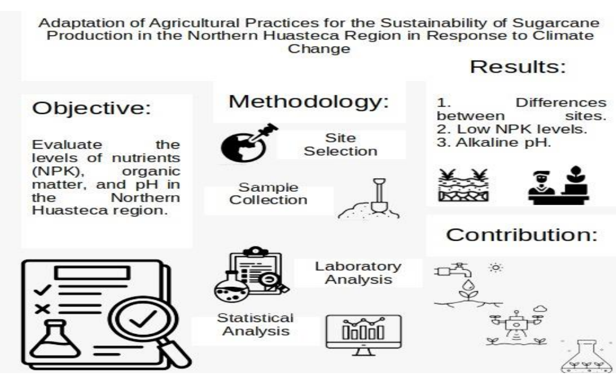
Abstract

Climate change poses significant challenges to agricultural production, requiring the adaptation of practices to ensure the sustainability of crops like sugarcane. This study focuses on the Huasteca Norte region of San Luis Potosí, Mexico, evaluating nitrogen, phosphorus, potassium, organic matter, and soil pH levels at 13 cultivation sites. Data reveal suboptimal NPK levels at most sites, indicating the need for improved nutrient management. Proposed strategies include the use of controlled-release fertilizers, efficient irrigation, and cover crops to enhance nutrient and water retention in the soil. The results highlight the importance of adopting a proactive and adaptive approach to agricultural management to address the challenges of climate change and ensure the sustainability of sugarcane production in the region.



Agriculture practices, Sustainability, Sugar cane

Resumen

El cambio climático impone desafíos significativos a la producción agrícola, requiriendo la adaptación de prácticas para asegurar la sostenibilidad de cultivos como la caña de azúcar. Este estudio se centra en la región Huasteca Norte del Estado de San Luis Potosí, México, evaluando los niveles de nitrógeno, fósforo, potasio, materia orgánica y pH del suelo en 13 sitios de cultivo. Los datos revelan niveles subóptimos de NPK en la mayoría de los sitios, indicando la necesidad de mejorar la gestión de nutrientes. Se proponen estrategias como el uso de fertilizantes de liberación controlada, riego eficiente y cultivos de cobertura para mejorar la retención de nutrientes y agua en el suelo. Los resultados subrayan la importancia de adoptar un enfoque proactivo y adaptativo en la gestión agrícola para enfrentar los retos del cambio climático y asegurar la sostenibilidad de la producción de caña de azúcar en la región.

Prácticas agrícolas, Sostenibilidad, Caña de azúcar

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Introduction

Sugarcane production in the Northern Huasteca Region of Mexico, an essential agricultural activity that has been historically important and has undergone various social and economic transformations (Pereda, 2016), faces significant challenges due to current agricultural practices and the effects of climate change. The latter is severely affecting agricultural production in the region, with increases in temperature, rainfall variability and extreme events such as prolonged droughts, which put the productivity of sugarcane crops at risk (Linnenluecke et al., 2018; Marin et al., 2013; Biggs et al., 2011; Zhao & Li, 2015). These changes directly impact soil quality and the availability of essential nutrients for sugarcane growth. In addition, the increase in extreme weather events, such as storms and floods, is causing increased soil erosion, decreasing soil fertility and its capacity to retain water and nutrients (Sundara et al., 1990; Castro et al., 2023).

In the Huasteca Potosina, agricultural soils present various limitations that affect their fertility. Soil degradation, mainly due to prolonged monoculture practices and lack of adequate nutrient management, is a recurrent problem (Castro et al., 2023).

Current agricultural practices are not only depleting soil resources, but also increasing its vulnerability to climate change. Soils show organic matter depletion, acidification and nutrient imbalances, which negatively affect the productivity of sugarcane crops (Kandhro et al., 2021). Organic matter is crucial for soil health as it improves soil structure, increases water holding capacity and facilitates nutrient availability. However, the reduction of organic matter due to intensive agricultural practices is leading to a decline in soil quality in the region (Castro et al., 2023; Dinka & Dawit, 2019).

Prolonged droughts and rainfall variability are increasingly frequent phenomena due to climate change and represent a considerable challenge for agriculture in the region. Lack of adequate water not only reduces crop productivity, but also exacerbates soil degradation and loss of essential nutrients (Linnenluecke et al., 2018; Biggs et al., 2011; Zhao & Li, 2015).

This scenario raises an urgent need to review and improve current agricultural practices to ensure the long-term sustainability of agricultural production in the Huasteca Potosina. Inefficient irrigation practices and excessive use of chemical fertilisers are contributing to soil salinisation and water pollution, further aggravating the situation (López Álvarez et al., 2015; Kusumawati et al., 2019).

A critical analysis of the elements that make up soil fertility in the region reveals that organic matter, soil pH and levels of nutrients such as nitrogen (N), phosphorus (P) and potassium (K) are key parameters that require proper management. Organic matter is crucial for water and nutrient retention, and its depletion significantly reduces the soil's capacity to support healthy crops (Castro et al., 2023).

Soil acidification, which affects nutrient availability, is another critical problem that needs to be addressed through more sustainable soil management practices (Kandhro et al., 2021). Imbalance in N, P and K levels, often caused by over- or under-application of fertilisers, also contributes to declining soil fertility (Pang et al., 2021; Zhang et al., 2019).

Assessment of these parameters at 13 sites in the Huasteca Potosina has revealed that current agricultural practices are not sustainable and are leading to progressive soil degradation. Soils show low levels of organic matter and imbalances in NPK levels, reflecting compromised soil fertility and reduced capacity to support agricultural production (Sundara et al., 1990; Dominy et al., 2002; Pang et al., 2021).

These problems are closely linked to monoculture practices and inefficient use of fertiliser and water resources (Castro et al., 2023; Kusumawati et al., 2019; Mitter et al., 2021). Monoculture, in particular, is associated with decreased soil biodiversity and increased pests and diseases, which in turn reduce crop productivity (Dominy et al., 2002; Madamombe et al., 2024).

It is crucial to recognize the need to implement sustainable agricultural practices that improve soil health and increase soil resilience to climate change.

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Strategies such as the use of controlled-release fertilizers, efficient irrigation techniques and the incorporation of cover crops can significantly improve soil structure, increase organic matter and reduce erosion (Kandhro et al., 2021; Dinka & Dawit, 2019; Mitter et al., 2021). The use of controlled-release fertilizers allows a gradual release of nutrients, improving their efficiency and reducing the need for frequent applications (Dinka & Dawit, 2019; Pang et al., 2021). Efficient irrigation techniques, such as drip irrigation, optimize water use and improve crop resilience to drought (Castro et al., 2023; Hussen, 2022). Cover crops improve soil structure, increase organic matter and reduce erosion, contributing to long-term sustainability (Kusumawati et al., 2019; Madamombe et al., 2024). In addition, crop rotation can help break pest and disease cycles, improve soil structure and increase biodiversity, which in turn improves the resilience of the farming system (Haque et al., 2023).

The incorporation of advanced technologies, such as remote sensing and the use of in-field sensors, can also play a crucial role in the sustainable management of sugarcane production. These technologies enable real-time monitoring of soil and weather conditions, facilitating informed and timely decisions to optimise agricultural management practices (Shukla et al., 2020; Haque et al., 2023; Pensado, et al., 2022). Integrating these technologies with traditional agricultural practices can offer a holistic and effective approach to meet the challenges of climate change (Kandhro et al., 2021; Madamombe et al., 2024). For example, soil moisture sensors can provide accurate data on soil water content, allowing farmers to adjust their irrigation practices to maximise water use efficiency (Shukla et al., 2020; Hussen, 2022). In addition, it is important to consider the role of education and training in promoting sustainable agricultural practices. Training programs for farmers can provide the knowledge and skills needed to implement sustainable and adaptive management practices. These programs should include modules on nutrient management, efficient water use, soil conservation and climate change adaptation, among other relevant topics (Dinka & Dawit, 2019; Hussen, 2022). The creation of farmer-to-farmer knowledge-sharing networks can also facilitate the dissemination of successful practices and innovation in farm management (Dominy et al., 2002; Pang et al., 2021).

Continuing education and training in the use of new technologies and sustainable practices are essential to improve the adoption of these practices among local farmers (Zhang et al., 2019; Mitter et al., 2021).

Collaboration between research institutions, local governments and farmer organizations is one strategy to develop and implement innovative and effective solutions to address the challenges of climate change in agriculture (Marin et al., 2013; Zhang et al., 2019; Mitter et al., 2021). Further research is needed to assess the impact of extreme weather events on sugarcane production and the effectiveness of integrated water resources management strategies. It is also crucial to investigate the long-term sustainability of different fertilization practices and how to overcome barriers to adaptation through increased institutional support and resources for farmers (Hussen, 2022). Cooperation between these different actors can facilitate the implementation of more sustainable agricultural policies and practices that benefit both farmers and the environment (Kusumawati et al., 2019).

The aim of this article is to provide a critical analysis of the elements that shape soil fertility in the Huasteca Potosina under the current agricultural model. Emphasis will be placed on the vulnerability of the region to climate change, prolonged droughts and current agricultural practices. Through this analysis, the aim is to raise awareness among farmers of the imperative need to adopt sustainable agricultural practices that will maintain economic systems without collapsing the environment. By providing evidence-based guidance, this article aims to help sugarcane farmers understand and address the challenges of climate change with effective and sustainable strategies, thus promoting agricultural production that is both economically viable and environmentally responsible.

Methodology

Selection of Sampling Sites

Sampling sites were selected following rigorous scientific criteria to ensure that the samples were representative of the characteristics of the Northern Huasteca Region.

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Variability in soil types, land use and environmental conditions were considered. Specific criteria included edaphic heterogeneity, spatial distribution of agricultural practices and accessibility of sites.

Thirteen sites strategically distributed in five different municipalities were selected, covering a wide range of agricultural conditions typical of the region. Figure 1 shows the location map of the sampling sites, clearly indicating the distribution and specific characteristics of each site.

Box 1

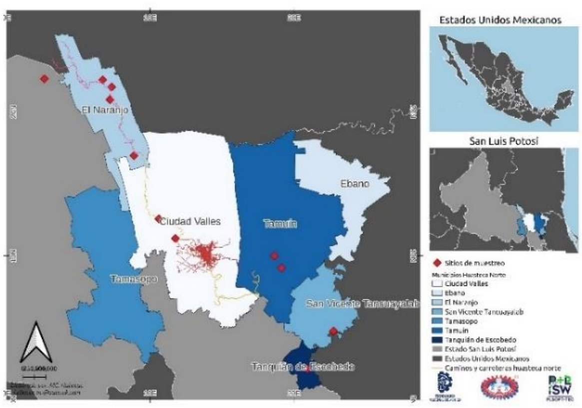

Figure 1

Map of the location of sampling sites in the Huasteca Potosina region

Sampling

Soil samples were collected following standardized protocols to minimize contamination and ensure sample integrity (ISO 10381-1, 2002). At each site, composite samples were taken from several sub-samples collected at different depths (0-30 cm), mixing them appropriately to obtain a representative sample from each location. Samples were labelled and stored under controlled conditions until analysis at the Environmental Research and Monitoring Laboratory of the Tecnológico Nacional de México Instituto Tecnológico de Ciudad Valles.

The labelling of the samples included key elements such as the sampling site code, the date of collection, the depth of the sample and the name of the collector.

In addition, each label contained a QR code to facilitate traceability and access to detailed information on sampling conditions and procedures followed.

Organic Matter Analysis

Quantification of organic matter in the soil was carried out by the calcination method using a muffle (Nelson & Sommers, 1996). This method involves the combustion of organic matter at high temperatures (550°C) until a constant weight is reached. Initially, the dried soil samples were weighed and then placed in a muffle furnace. After complete combustion of the organic matter, the samples were reweighed, and the organic matter content was determined as the weight loss after calcination. This procedure is widely recognised for its accuracy and reliability for the determination of soil organic content (Heiri et al., 2001).

Determination of soil pH

Soil pH was measured by solubilizing the soil in a distilled water solution, following the method described by McLean (1982). For this, a suspension of soil and water was prepared in a ratio of 1:2.5 (weight/volume), and the mixture was stirred for 30 minutes.

Subsequently, the suspension was allowed to stand and the pH of the supernatant solution was measured using a calibrated pH meter. This method is standard for the evaluation of soil pH and provides consistent and reproducible results.

NPK analysis

The determination of nitrogen (N), phosphorus (P) and potassium (K) levels in the soil was carried out using the NPK HI3896 kit, which allows the simultaneous measurement of these essential nutrients using colorimetric techniques specific to each (Johnston & Richards, 2003).

Soil samples were prepared according to the kit instructions, and readings were taken following the procedures indicated by the manufacturer. Specific chemical reactions within the kit produce colour changes in the presence of the nutrients, which are then measured and interpreted to quantify N, P and K levels.

The results obtained provide an accurate assessment of NPK levels in soil samples, fundamental to the interpretation of soil fertility and health at sampling sites.

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Statistical analysis of the data

The data obtained were statistically analyzed using Google Colab with Python, ensuring a collaborative and reproducible environment for data analysis. Various statistical techniques were employed to analyse the data and assess the spatial and temporal variability of soil properties. Initially, the assumptions of normality and homogeneity of variance were checked using Shapiro-Wilk and Levene tests, respectively (Shapiro & Wilk, 1965; Levene, 1960).

To compare the levels of %MO, pH, N, P and K between the different sampling sites, one-way analysis of variance (ANOVA) was applied and where necessary because the assumptions of normality or homogeneity of variance were not met, equivalent non-parametric tests (Kruskal-Wallis) were performed, followed by Tukey's post hoc tests to identify significant differences between means (Tukey, 1949). In addition, principal component analysis (PCA) was used to identify patterns and relationships between measured variables and sampling sites, providing a holistic view of the data structure. (Jolliffe, 2002).

All statistical analyses were performed using Python libraries such as NumPy, pandas, SciPy and Scikit-learn, facilitating efficient calculations and data visualization. Statistical results were presented in the form of tables and graphs, highlighting significant differences and trends observed in the data (Oliphant, 2006).

This methodology ensures that the data obtained are representative and reliable, providing a solid basis for the assessment of soil conditions in the Northern Huasteca Region and their relationship to the sustainability of sugar cane production in the face of climate change.

Results

Organic Matter and Soil pH

The results obtained show significant differences in soil pH and organic matter (%MO) levels (Figure 2 and Figure 3) between the municipalities of the Northern Huasteca region.

Box 2

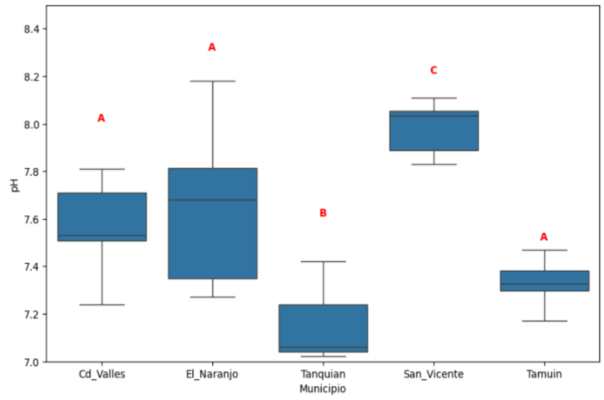

Figure 2

Distribution of pH by municipality (Northern Huasteca Region). Note: Different letters indicate statistically significant differences ($p<0.005$)

Box 3

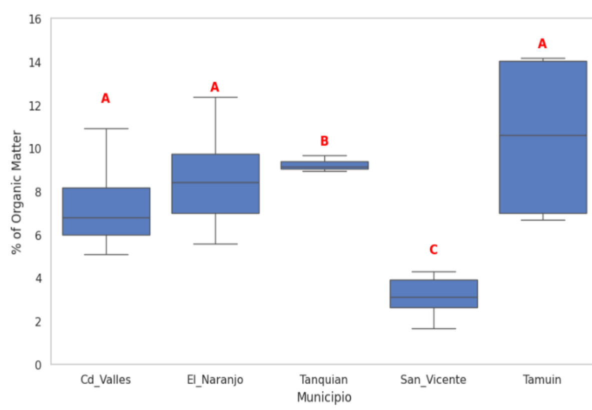

Figure 3

Distribution of % organic matter by municipality (Huasteca Norte Region). Note: Different letters indicate statistically significant differences ($p<0.005$)

Table 1 summarises the average organic matter and pH values of the 13 sites located in the five sampled municipalities. Tamuín presents the highest average organic matter content (10.50%) with a standard deviation of 3.92%, while San Vicente shows the lowest content (3.14%) with a standard deviation of 0.99%.

In terms of pH, San Vicente has the highest average value (7.99) with a standard deviation of 0.12, and Tanquián presents the lowest pH (7.17) with a standard deviation of 0.22.

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Box 4

Table 1

Distribution of % organic matter by municipality (Huasteca Norte Region). Note: Different letters indicate statistically significant differences (p<0.005)

Municipality	Mean MO (%)	Std MO (%)	Mean pH	Std pH
Cd. Valles	7.43	2.08	7.55	0.19
El Naranjo	8.68	2.11	7.64	0.30
San Vicente	3.14	0.99	7.99	0.12
Tamuín	10.50	3.92	7.33	0.10
Tanquián	9.25	0.36	7.17	0.22

Analyses of variance (ANOVA) for %MO and pH (Tables 2 and 3) confirm that the differences observed between municipalities are statistically significant, with p-values less than 0.00005 in both cases.

Box 5

Table 2

ANOVA for %MO

Source	Sum of Squares	df	F	p- valor
Municipality	192.8386	4	9.1720	0.00004
Residual	178.7103	34	-	-

Box 6

Tabla 3

ANOVA para pH

Source	Sum of Squares	df	F	p-valor
Municipality	1.9286	4	9.1806	0.00004
Residual	1.7857	34	-	-

Organic matter is crucial for soil health as it improves soil structure, retains moisture and nutrients, and promotes biological activity (Lal, 2004). High levels of organic matter in Tamuín could be related to more sustainable agricultural practices or less intensification of land use.

In comparison, studies in other tropical regions have shown that the addition of organic residues and the use of cover crops can significantly increase soil organic matter (Ghimire et al., 2017). Soil pH is also an important indicator of soil fertility. pH values close to neutral (6.5-7.5) are ideal for the availability of most nutrients (Brady & Weil, 2008). The results show a variability in pH that could be influenced by the application of alkaline or acidic amendments, soil management practices, and intrinsic soil characteristics at each site.

Nitrogen (N), Phosphorus (P) and Potassium (K) levels

The determination of nitrogen (N), phosphorus (P) and potassium (K) levels in the soil was carried out using the NPK HI3896 kit, which allows the simultaneous measurement of these essential nutrients by means of colourimetric techniques specific to each one. Soil samples were prepared according to the kit instructions, and readings were taken following the procedures indicated by the manufacturer. The results obtained are qualitative on a scale ranging from 1 (Very low presence) to 4 (Very high presence), and indicate that all sites have suboptimal presence of the NPK nutrients required for sugar cane cultivation.

Similar studies have shown that NPK deficiency in agricultural soils is common in tropical regions, affecting crop productivity (Fageria & Baligar, 2008). Low availability of these nutrients may be due to leaching, soil erosion and insufficient fertilizer application. To improve soil fertility, it is essential to adopt nutrient management practices that include balanced fertilizer application and the use of biofertilizers (del Pozo et al., 2019).

Analysis of variance (ANOVA and Kruskal-Wallis)

Analysis of variance (ANOVA) revealed significant differences in %MO, pH, N, P and K (Kruskal-Wallis) between sampling sites ($p < 0.05$). Tukey's post hoc tests indicated that Tamuín is significantly different from other municipalities in terms of organic matter and pH. Likewise, San Vicente showed significant differences in N and K levels compared to other sites as shown in Table 4.

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Box 7

Table 4

Non-Parametric Tests (Kruskal-Wallis)

Variable	Kruskal-Wallis statistic	p-valor	Significant
N	2.2472	0.6904	No
P	8.0000	0.0916	No
K	5.5000	0.2397	No

Principal Component Analysis (PCA)

Principal component analysis (PCA) identified clear patterns in the relationship between measured variables and sampling sites. The first two principal components explained 75% of the total variability in the data. The first component was highly correlated with N and K levels, while the second component showed a strong correlation with pH and organic matter. Figure 4 presents the PCA biplot, highlighting the grouping of the sampling sites according to their edaphic characteristics.

Box 8

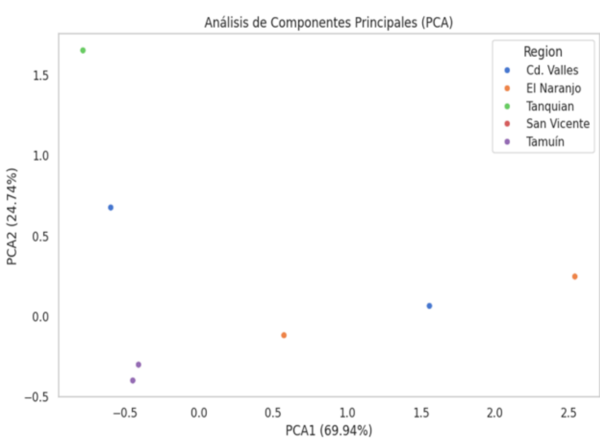

Figure 4

Principal Component Analysis (PCA) in municipalities of the Huasteca Norte region

These patterns suggest that variability in soil properties is influenced by multiple factors, including soil management practices and site-specific environmental conditions. Previous studies have shown that principal component analysis is an effective tool for identifying and explaining spatial variability in soil properties (Shukla et al., 2006).

Conclusions

This study has revealed significant variations in soil properties, specifically in the levels of organic matter (%MO), pH, nitrogen (N), phosphorus (P) and potassium (K), in the Northern Huasteca region. The results underline the need to adopt more sustainable and adaptive agricultural practices to face the challenges of climate change and improve the productivity of sugarcane crops.

In terms of organic matter, Tamuín presented the highest levels, while San Vicente showed the lowest. Organic matter is fundamental to soil health, as it improves soil structure, retains moisture and nutrients, and promotes biological activity. High levels of organic matter in Tamuín suggest more sustainable agricultural practices, while low levels in San Vicente indicate possible soil degradation. To improve organic matter in areas with low levels, it is essential to consider the addition of organic residues and the use of cover crops, practices that have been shown to be effective in other studies (Ghimire et al., 2017).

Soil pH varied significantly between municipalities, with San Vicente showing the highest values and Tanquian the lowest. pH values close to neutral are ideal for the availability of most nutrients (Brady & Weil, 2008). Variations in pH can influence nutrient availability and thus crop productivity. The alkalinity observed in St Vincent may be negatively affecting the availability of certain nutrients, requiring adjustments in soil management practices, such as the application of acid amendments.

Soil levels of nitrogen, phosphorus and potassium were suboptimal at all sampling sites, indicating a general deficiency of these essential nutrients. Low NPK availability may be due to leaching, soil erosion and insufficient fertilizer application.

This deficiency is a common problem in tropical regions and significantly affects crop productivity (Fageria & Baligar, 2008). To address this deficiency, the adoption of nutrient management practices including balanced fertilizer application and the use of biofertilizers is recommended (Del Pozo et al., 2019).

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Analysis of variance (ANOVA) revealed significant differences in %MO, pH, N, P and K levels among sampling sites. Tukey's post hoc tests confirmed that Tamuín is significantly different from other municipalities in terms of organic matter and pH. San Vicente also showed significant differences in N and K levels compared to other sites. These findings highlight the importance of adapting soil management practices to the specific conditions of each municipality to maximise soil fertility and crop productivity.

Principal component analysis (PCA) identified clear patterns in the relationship between measured variables and sampling sites. The first two principal components explained 75% of the total variability in the data, with the first component highly correlated with N and K levels, and the second component showing a strong correlation with pH and organic matter. These patterns indicate that variability in soil properties is influenced by multiple factors, including soil management practices and site-specific environmental conditions (Shukla et al., 2006).

This study provides an assessment of soil conditions in the Northern Huasteca region and suggests the need to implement sustainable and adaptive agricultural practices to improve soil health and increase resilience to climate change. The adoption of practices such as the addition of organic residues, the use of cover crops, and the balanced application of fertilisers can significantly improve soil fertility and crop productivity. In addition, the use of advanced technologies, such as remote sensing and in-field sensors, can facilitate real-time monitoring of soil and weather conditions, optimizing agricultural management practices. Collaboration between farmers, researchers and policy makers will be crucial to develop and implement these strategies, thus ensuring the long-term sustainability of agricultural production in the Northern Huasteca region.

Declarations

Conflict of interest

The authors declare that they have no conflicts of interest. They have no known competing financial interests or personal relationships that might have appeared to influence the article reported in this paper.

Authors' contribution

Each researcher's contribution to each of the points developed for this paper is listed below:

Lorenzo-Márquez, Habacuc: Designed the project idea, methods and applied research techniques. He designed the instrument for the collection of information in the field, supported the field sampling and laboratory analysis, carried out the data analysis and systematization of results, as well as writing the article.

Wong-Arguelles, Cynthia: Supported in the application of the research methods and techniques, contributed to the laboratory analysis and the revision of the article.

Acosta-Pintor, Dulce Carolina: Contributed to the research design, type of research, laboratory analysis, analysis of data collected in sampling and writing of the article.

Mojica-Mesinas, Cuitláhuac: supported field sampling, data collection and laboratory analysis. Worked on the writing of the article.

Availability of data and materials

All data used for this research were derived from our own data analysis, no information from third parties was used.

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Abbreviations

ANOVA	Analysis of Variance
ISO	International Organization for Standardisation
K	Potassium
N	Nitrogen
NPK	Nitrogen, Phosphorus, Potassium
OM	Organic Matter
P	Phosphorus
PCA	Principal component analysis
pH	Hydrogen potential
PRODEP	Programme for the Professional Development of Teachers
QR	Quick Response Code

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Background

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