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Community-based strategies for climate adaptation in rural Mexico: The case of the Huasteca Potosina

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ABSTRACT

For rural communities engaged in rainfed agricultural systems, climate variability and change are substantial concerns. In response, many communities have implemented strategies to face climate challenges. This study examines the strategies implemented by indigenous farmers involved in rainfed agriculture systems to address the impacts of climate variability and change in four communities in the Huasteca Potosina, Mexico. The research, based on participatory methods, included in-depth interviews with key actors, stakeholder surveys, participatory workshops, and participant observation, as well as triangulation of information. In the study area, erratic rainfall, rising temperatures, and prolonged droughts are the main climate changes that threaten the livelihoods, local economies, and cultural identities of the indigenous farming communities. The most widely adopted strategies to address adverse climate conditions included soil conservation, land management, and participation in working groups. Emerging strategies involve training and capacity building supported by government programs. Necessary but less common practices were mainly associated with water management. The government programs have promoted several of these strategies, while others have emerged from empirical knowledge. A close relationship was found between traditional knowledge, institutional frameworks, and the availability of resources of time and money for the implementation of these strategies. Consolidation of the most effective strategies requires institutional support to be maintained, so changes in current agricultural policy could negatively impact many advances. Effective adaptation strategies in the face of expected climate change must consider the specific socioeconomic, cultural, and environmental conditions.

Keywords: Adaptation, agroecology practices, environmental governance, empirical knowledge..

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SIGNIFICANCE STATEMENT

This qualitative study evaluates the implementation of community-based climate change adaptation strategies in indigenous farming communities that depend on rainfed agriculture. The widely adopted, emerging, and aspirational strategies to address adverse climate conditions synthesize the three main types of practices. These strategies are evidence of the interactions between traditional knowledge, institutional support, and resource availability. The most widely adopted strategies include soil conservation, land management, and participation in working groups. Technical support for water management and training for young farmers are highly recommended, as these are major concerns. Effective adaptation strategies in the context of climate change must consider the specific socioeconomic, cultural, and environmental conditions.

INTRODUCTION

It is widely recognized that climate change is the major threat to biodiversity, natural resources, and human livelihoods (Altieri et al. 2020; Mendoza-Ponce et al. 2018; Prieto-Torre et al. 2021; Tamru et al. 2025). Expected changes mainly involve rising temperatures, alteration of precipitation, and more frequent extreme weather events, among others (FAO 2021; INECC 2019; Smith et al. 2014).

Such changes may create opportunities for some communities, while simultaneously increasing vulnerability for others, particularly marginalized populations (Fierros and Ávila-Foucat, 2017; Mertz et al. 2009; Morales-Casco and Zúniga-González 2016). Although it is recognized that climate change will broadly impact natural resources, food security, and public health, the spatial and temporal impacts at different scales remain uncertain (Adger et al. 2011; Nelson et al. 2010).

In general, the agricultural sector is particularly vulnerable, because climate variability and change reduce yields, which seriously affects household incomes (Lucero et al. 2022; Tamru et al. 2025). Rural communities engaged in rainfed agricultural systems are particularly vulnerable to these climate alterations because their livelihoods depend on natural resources and climate stability. Current and future climate alterations will result in unpredictable harvests and economic uncertainty (Altieri et al. 2020).

In the present day, there are emerging technologies that offer alternatives for mitigating climate change, however; they are not affordable for most of the poorest communities (Melo et al. 2016). For indigenous populations in particular, limited access to resources and decision-making processes exacerbates their prevalent economic inequalities. However, their traditional knowledge and ancestral practices are emerging as an alternative way to build climate resilience and adaptability (Altieri et al. 2020; Tengö et al. 2017).

Integration of local knowledge and novel strategies can improve local livelihoods and strengthen the adaptive capacity of the poorest productive sectors. To achieve this, it is fundamental to empower marginalized groups, reinforce cultural identity, and enhance local governance structures through active community participation (Brauer et al. 2024; INECC 2019; Reyes-Hernández et al. 2022). However, effective adaptation requires a deep understanding of the dynamics of the social and ecological context (Newsham et al. 2018).

In tropical regions where livelihoods are closely linked to natural cycles, ethnobiological knowledge plays a critical role in design adaptation strategies to address climate change. In the Huasteca Potosina region, traditional agricultural systems that integrate trees, cultivated plants, cultural practices, and efficient use of space reflect a close relationship between people and their environment (Trinidad et al. 2021). However, the region is also home to more than 70% of the poorest and most marginalized people of the state of San Luis Potosí (INEGI 2020). The situation is exacerbated by future climate scenarios that predict a 4 ºC rise in maximum temperatures and a 10% reduction in precipitation (INECC 2019; SEGAM 2018). For local inhabitants, adaptation is a matter not only of survival, but also of social and environmental justice.

The objective of this study was to examine the strategies implemented by indigenous farmers engaged in rainfed agriculture to address the impacts of climate variability and change in four communities in the Huasteca Potosina, Mexico. The questions that guide the research were: How do indigenous farmers perceive and react to climate variability and change? What strategies have been implemented and what are their origins? Which strategies have been most effective?

MATERIAL AND METHODS

Study Area

The Sierra Citricola-Piloncillera is located in the Huasteca Potosina, located in the northern part of Mexico. The region is characterized by intermountain valleys interspersed with low mountains with gentle slopes, at an average elevation of 400 m. The predominant climate is sub-humid warm (ACw), with an average annual temperature of 24 ºC and 1,500 mm

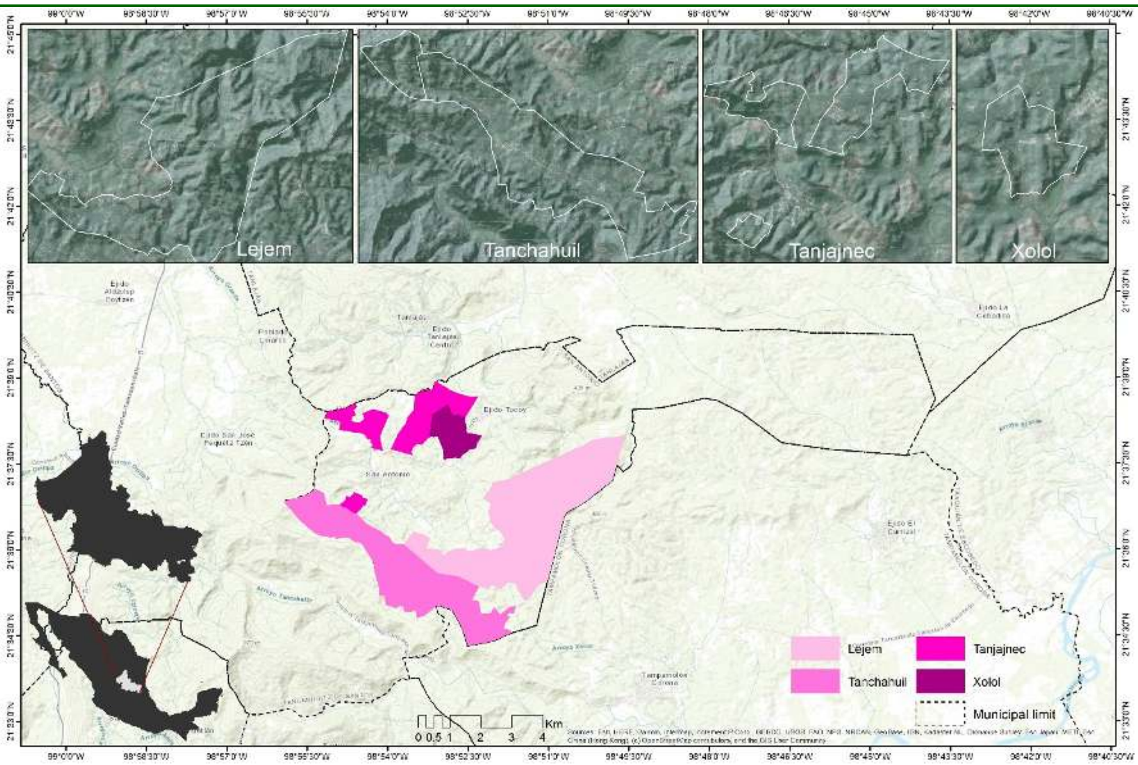

Figure 1. Location of the Lejem, Tanchahuil, Tanjajnec and Xolol communities in the Sierra Citricola-Piloncillera microregion, Huasteca Potosina region, Mexico.

average annual precipitation (INEGI 2003). Perennial rivers are nonexistent, and most streams are intermittent (Figure 1).

The municipality of San Antonio situated in the middle of the Sierra Citriciola-Piloncillera has a population of 9,300. According to the INEGI (2020), over 80% of the population is indigenous and belongs to the Tének ethnic group. The communities of San Antonio municipality are highly marginalized and entirely dependent on rainfed agricultural production. The two main agricultural products are maize (*milpa*) and sugarcane production for *piloncillo* (unrefined cane sugar). *Piloncillo*, produced in both molded and granulated forms, is the economic backbone and a symbol of identity. However, most of the producers lack the infrastructure and resources necessary to market the final product (Figure 2).

Lejem, Tanjajnec, Xolol, and Tanchahuil are located in the San Antonio municipality between 98°49'30" and 98°55'22" W and 21°34'45" and 21°39'05" N. These communities are representative of the socioeconomic, cultural, and environmental conditions that prevail in this region. In Mexico ejidos and agrarian communities are two forms of collective land tenure in which members have usufruct rights to land and water, with legal recognition by the Mexican government as agrarian nuclei (Perramond, 2008). The four communities face substantial deficiencies of primary services, such as education, drinking water, and health care services and were selected after an exhaustive fieldwork process.

Methodological procedure

To assess how residents perceive climate trend patterns, their impact on livelihoods, and the implemented strategies, we used participatory methods to gather information on perceptions of climate change, impact of drought, implications for livelihoods, and actions taken to address these challenges. This approach has been widely applied in rural contexts as valuable tool for diagnosis, planning, natural resource evaluation, and ethnobiological studies (Albuquerque et al. 2014; Brauer et al. 2024; Geilfus 2009; Reyes-Hernández et al. 2022; Sampaio et al. 2014; Vaca-Pardo and Reyes-Hernández 2021).

The first stage of the study involved 12 in-depth interviews with key informants in the municipality of San Antonio. Participants were selected for their experience with innovative cultural practices or for their roles as local decision-makers and local experts. The participants included local authorities (*comisarios* of each community), government program technicians (*Sembrando Vida* and *Producción para el Bienestar*),

Figure 2. A. Traditional maize production (*milpa*); B. Sugarcane production; C and D. Traditional molded piloncillo production; E. The *engavillado* technique to conserve soil moisture (placing sheaves on the ridges between furrows); F. Collective harvesting in a demonstration plot in Tanchahuil.

local organization leaders, and elderly farmers. Four women and eight men were interviewed.

The in-depth interviews revealed the general perception of climate variability and change as well as the primary challenges faced by agricultural production systems. In addition, we identified some innovations in agricultural techniques and the various actors in the *piloncillo* value chain. Some trigger questions were: What are the main climate challenges faced by agricultural producers? What initiatives have been developed to address climate variability and change? What innovations or technical adaptations are being implemented in agricultural systems?

The second phase included a survey applied to a random sample of 100 indigenous farmers who produce sugarcane and *milpa* for self-consumption. A total of 65 men and 35 women between 19 and 78 years old were surveyed. The survey was divided into four topics; general information, perceptions of climate variability, climate impacts, and practices implemented and their perceived effectiveness. The scale to qualify the effectiveness of each implemented strategy was very low, low, medium, high, or very high.

The survey enabled us to determine local perceptions of climate change and its impact on livelihoods, implemented strategies, and a qualitative assessment of their effectiveness. Some additional questions addressed potential agricultural practices to be implemented, support required for these, and necessary resources. In order to assess the participants' comprehension, question clarity, and average response time, a pilot test was conducted prior to application of the survey to the sampled respondents.

The questionnaire and the interview guide were based on previous studies carried out in the region (Farias 2022; Trinidad et al. 2021 Vaca-Genuit and Reyes-Hernández 2025) and information provided by the research project "*Adaptacion al cambio climático en comunidades rurales: Una aproximación desde la gobernanza ambiental"* [Adaptation to climate change in rural communities: An environmental governance approach].

Most of the indigenous farmers surveyed were involved in the *Producción para el Bienestar* government program. As part of the program, participants must regularly attend meetings to carry out activities such as training sessions, preparing inputs, evaluating results, exchanging experiences, and assessing new agricultural techniques. These meetings are facilitated by program technicians. Although this could have introduced selection bias, the participants provided valuable insights related to adaptation strategies to cope with climate change.

The third phase of the study involved the implementation of four participatory workshops. The workshops were held to address the themes of collective perception of climate change, and collective resilience strategies.

For the first theme, participatory mapping was the main tool employed. The activities included the use of land surface temperature (LST) maps derived from Landsat satellite imagery. In these maps, participants identified their agricultural plots and compared temperature values between 2023 and 2024 and the results of some strategies implemented. Critical areas for intervention or implementation of actions to mitigate adverse conditions were also identified (Figure 3A, 3B, 3D).

The second theme focused on hands-on training in agricultural practices and resilience building. Participants learned how to prepare and apply natural insecticides and organic fertilizers. These activities were complemented by on-site presentations in the field and corresponding evaluation in a demonstration maize plot at the end of the harvest (Figure 3C).

Additionally, at the request of local organizations, several materials were collaboratively designed to strengthen the marketing of granulated *piloncillo*, including labels, a brand name and tagline, visual identity for the product, and other elements to reinforce the value chain of granulated *piloncillo* (Figure 3F).

During the participatory workshops, two facilitators led the main activities, and two assistants recorded the participants' observations, interpretations, and interactions. The workshops averaged 25 participants (including women and men), most of whom were affiliated with the program or with the association dedicated to marketing granulated *piloncillo*. The average duration of these activities was three to four hours.

Participatory observation was conducted during the entire fieldwork period. The research team collaborated on sessions about fertilizer preparation and application, maize harvesting, and the production of molded and granulated *piloncillo*. They also observed the leadership of the *piloncillo* producers present their report of the association's activities.

Data Analysis

Data collected through in-depth interviews, surveys, and participatory workshops were analyzed using a mixed-methods approach.

Quantitative survey data were compiled in a database and examined through descriptive statistics such as frequencies, percentages, and cross-tabulations to identify patterns in perceptions of climate variability, number and type of adaptation practices, and the perceived effectiveness of the strategies implemented. Because this study aimed to provide a contextual understanding of climate change perception and adaptation dynamics, rather than make inferences or predictions, the surveys were analyzed using exclusively descriptive analysis.

The qualitative information derived from each in-depth interview was analyzed using thematic coding. The interviews were first transcribed. A matrix was constructed in Excel to manually code and organize interview extracts. Through repeated reading of the statements, this procedure allowed us to identify, compare, and structure significant topics. The categories of the analysis were climate perception, adaptation practices, alternatives and future strategies, institutional support, and vulnerabilities.

Figure 3. A B. Identification of plots threatened by high temperatures in LST maps; C. Fertilizer preparation training; D. Comparing LST in 2023 and 2024 and evaluation of severity; E. Representation of the essential elements of a traditional agricultural system; F. Designing visual identity and branding for granulated *piloncillo*.

The information obtained from the participatory workshops was organized and systematized according to the themes discussed, types of participants, and outcomes. This data provides valuable information related to collective actions, community-based adaptation practices, general concerns, and additional required strategies. The cartographic material generated by the participants included current spatial patterns of agricultural plots, critical areas due to LST values, areas of intervention, and implemented actions. The spatial information embodied in the maps was complemented with the notes collected by assistants (Figure 3E).

The final stage was the triangulation process. This approach combines several methods to analyze a research topic, integrating quantitative and qualitative focuses to strengthen and validate the data gathered (Albuquerque et al. 2014). To this end, information from the quantitative survey was cross-referenced with qualitative insights from the in-depth interviews. This information was then contrasted with information derived from participatory workshops and participant observation.

This procedure confirmed the effectiveness of the implemented strategies, enabled contradictory information to be discarded, and provided a more comprehensive understanding of the regional context. It also made it possible to identify coinciding and contextual factors that influence individual and collective responses to climate change and community aspirations.

RESULTS

Context of the communities

Among the indigenous farmers of the Sierra Citricola–Piloncillera, 80% of the residents belong to the Tének ethnic group. This generates additional barriers and complicates access to public services, education, and economic support programs. The strong dependence on self-consumption and subsistence agriculture limits income diversification. Moreover, inadequate road infrastructure limits market integration and raises production costs.

The government provides technical assistance through the *Producción para el Bienestar* and *Sembrando Vida* programs. *Producción para el Bienestar* was implemented in the communities of Tanchahuil, Tanjajnec, and Xolol. *Sembrando Vida* is active in Lejem and Tanchahuil. *Produccion para el Bienestar* aims to promote more sustainable agricultural systems by implementing agroecological practices that can enhance the well-being of households. It also promotes diversification of agricultural activities subject to conditional support. Training activities are carried out through the *escuelas de campo* (field schools) initiative.

The four communities differ significantly in both population size and geographical extent. Lejem is the largest settlement covering 1,359 ha and hosting 574 inhabitants (0.42 inhabitants/ha). Tanchahuil with 454 inhabitants and 934 ha, exhibits a similar population density (0.49 inhabitants/ha). Tanajnec, which has 540 inhabitants within a considerable smaller area (407 ha), shows a higher density (1.33 inhabitants/ha). Xolol, the smallest community in both population and area (228 inhabitants and 164 ha), has the highest population density (1.39 inhabitants/ha).

These differences are reflected in amount of land available per household: in Tanchahuil and Lejem farmers typically own three to four hectares, while Tanjajnec they own two hectares, and in Xolol approximately one hectare. Due to historical agricultural traditions, 65% of respondents were men and the rest were women. The average age was 55. The youngest indigenous people interviewed were under 40 years old. Although 90% of the participants had completed middle school, access to higher education remains limited. As in the rest of the Huasteca region, inhabitants can only access higher education in the main urban centers. Limited access to government support, deficient public services, and insufficient infrastructure complicates their local context.

However, differences in social indicators among the four communities may affect their ability to respond to climate-related stressors. Lejem has the lowest degree of social inequality because as a smaller percentage of its households lack basic services such as safe drinking water, adequate sanitation, and electricity. In contrast Xolol shows a markedly higher level of social inequality, due to significant deficits in elementary education, healthcare, and basic household infrastructure. Tanchahuil and Tanjajnec occupy an intermediate position regarding these indicators. These disparities in social deprivation imply varying degrees of susceptibility to the impacts of climate variability and change.

The social inequalities in Xolol, may exacerbate the community´s vulnerability given the limit access to sanitation, clean water, energy resources and the reduced amount of available land. Moreover, the lack health services and incomplete basic education may reduce community awareness and constrain adaptive decision-making abilities. Even in Lejem, remaining deficiencies could increase exposure to heat stress, disease, and food insecurity.

Climate change perception and its impacts

According to the frequency of the surveyed respondents, rising temperatures (87) and changes in rainfall patterns (61) are the main indicators of climate change. Older farmers tended to emphasize long-term environmental changes such as variations in rainfall patterns and alterations in seasonal cycles. In contrast, younger participants (<50 years old) mentioned the presence of extreme weather events such as storms, hailstorms, and heat waves more frequently.

In terms of gender roles, women emphasized the scarcity of water associated with droughts, probably because they are responsible for providing this resource to the household. Men focused primarily on changes in rainfall patterns, associated mainly with agricultural activities.

In general, the principal concern among all respondents was related to the impact of climate change on their livelihoods. The most frequently cited issue was reduction in agricultural productivity (76), followed by the emergence of new pests (65) and crop diseases (64) (Figure 4). Key actors confirmed that pests and diseases have become more frequent and severe in recent years, particularly during prolonged drought periods.

The next most frequently stated concerns included a decrease in *piloncillo* production (59), alteration of the planting calendar due to changes in rainfall patterns (58) and generalized water shortages (56). Less frequent issues which were recognized but not perceived as immediate threats were loss of soil moisture (25) and the reduction in sugarcane juice content (22) (Figure 4).

Some responses reflect the farmers' empirical knowledge while other reflect the influence of government technicians. In this regard, perceptions related to water shortages, reduced sugarcane productivity, and increased pests would be linked to the empirical knowledge. Concerns such as biodiversity loss, soil erosion, and reduced soil moisture appear to be associated with extension activities.

During the participatory workshops, it was evident that the indigenous farmers were concerned about how the reduced water availability had severely impacted the productivity of *milpa* and sugarcane. They identified months with unusually high temperatures and months with markedly reduced precipitation. Older participants pointed out that the rainfall pattern has shifted drastically. The rainy season which usually started in April and extended to October now begins in mid-June. Technicians and local authorities agreed with these observations throughout the Huasteca region.

The most critical plots and areas with respect to land surface temperature were identified using LST maps. These maps revealed that several of the implemented strategies are insufficient. However, this is also associated with multiple environmental factors such as slope orientation, elevation, forest canopy, and proximity to roads.

Climate impacts also included an increase in mosquitoes that transmit diseases, such as dengue, and to the faster spread of these vectors. Household water scarcity and reduction in biodiversity were also mentioned. In the four study communities, local health centers are nearly nonexistent, which add stress and imposes extra costs on households.

Implemented adaptation strategies

Indigenous farmers have adopted a variety of sustainable practices to enhance long-term agricultural resilience and mitigate the adverse effects of climate variability. Government programs have played a crucial role in these strategies by providing economic incentives and the technical assistance. The implemented strategies were classified into three main groups (Figure 5):

1. Widely adopted (65–80 responses). Related to soil conservation, land management and collaboration in farmers' associations. These include employing natural fertilizers (B5), planting trees or shrubs around cultivation areas as windbreaks (B4), participating in cooperatives or associations (D3), planting legumes or cover crops during fallow periods (B6), and planting intercropping legumes (C4), and leaving crop residue for soil protection (B8). The high frequency reflects the consolidation of traditional agricultural practices and the influence of external programs (D3).

2. Emerging (40–60 responses). They were mainly associated with training and capacity-building supported by government programs. These consist of participation in workshops or different training activities (D1), establishing seed and knowledge exchange networks (D4), employing contour cropping (B9), incorporating fruit trees into the plots (C2), transmitting traditional knowledge (D2), and implementing contour barriers (including the *engavillado* technique) to conserve soil moisture (B2). These moderately adopted practices are being gradually incorporated, but their implementation still depends on institutional support.

3. Aspirational (fewer than 30 responses). Most of these strategies, recognized as necessary but barely implemented, were related to water management. These include elaboration and employing of naturales pesticides (C5), establishing seed banks of resilient varieties (C3), applying charcoal to soil to improve water and nutriment retention (B7), planting vegetation in ditches (A6), and implementing rainwater harvesting systems (A1). Although most of these activities are potentially beneficial, they remain largely unadopted due to high costs and limited technical knowledge.

Effectiveness of adaptation strategies

Restoring soil fertility by incorporating compost and manure, and natural pest control methods based on sulfur-lime mixtures were identified as key strategies. Additional effective practices included soil conservation through reforestation, the use of cover crops, and contour farming on sloped terrain. According to the participants, these practices reduce erosion, improve rainwater infiltration, and increase soil fertility.

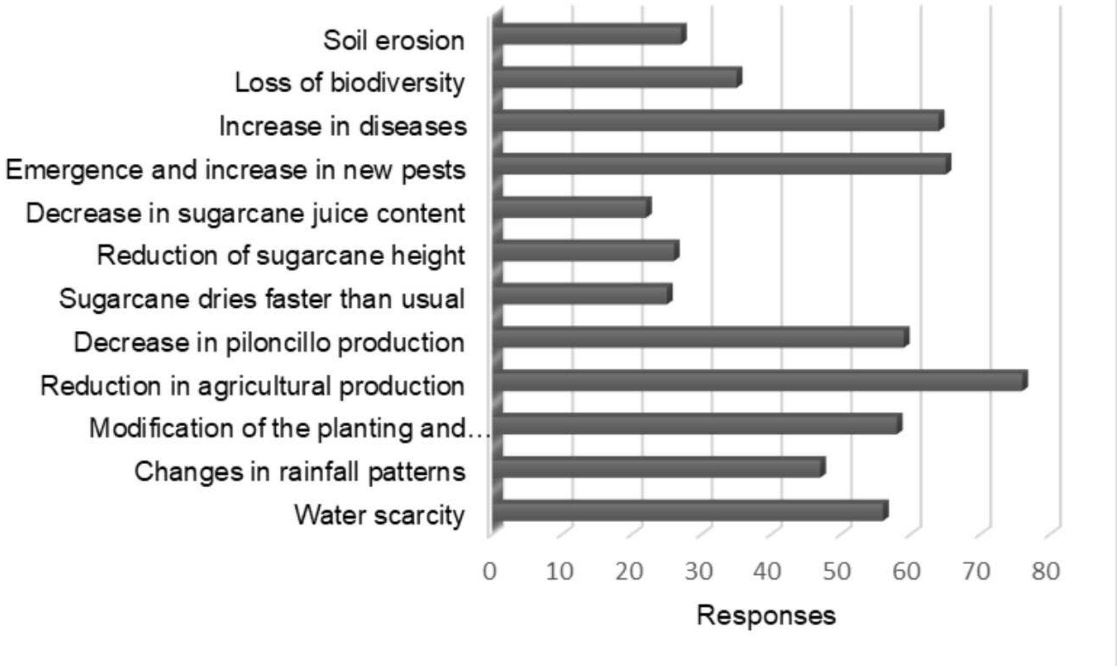

Figure 4. Survey responses on climate change concerns.

The most important observation was that these methods of soil conservation reduce dependence on chemical inputs. The indigenous farmers collectively agreed on the effectiveness of these techniques (Table 1).

Most of the people surveyed, including workshop participants and those involved in informal conversations, recognized that implementing agroforestry systems, soil conservation practices, and some irrigation methods has improved agricultural production despite droughts. However, some complaints have emerged about the number of activities required by the government programs. It is evident that financial support is needed to achieve certain goals. Other highly effective strategies included working groups, associations and modified daily fieldwork schedules. Although water management practices were recognized as effective, few indigenous farmers have implemented these strategies. Participants admitted that local efforts alone are insufficient, therefore external support and financial assistance are required (Table 1).

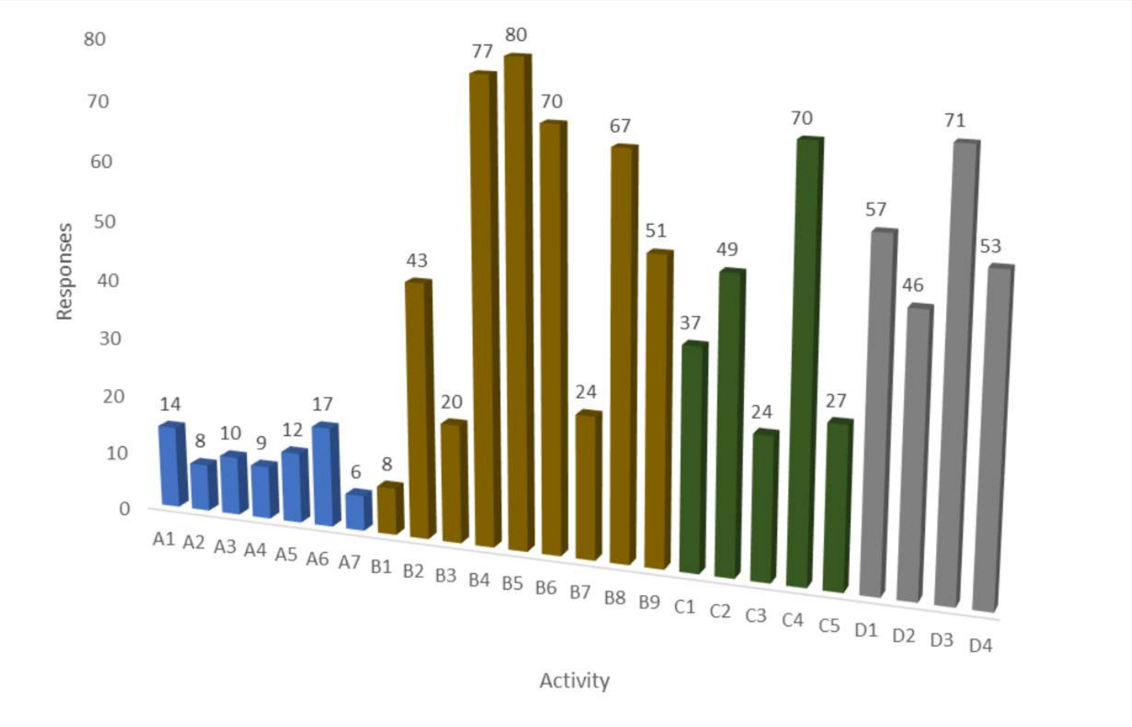

Figure 5. Climate adaptation activities reported by respondents, grouped by category: water management (A), soil conservation (B), crop diversity (C) and resilience, knowledge, organization, and community (D). A1: Rainwater harvesting system, A2: Gutters to storage tanks, A3:Terrain modification for water retention, A4: Identify low-risk areas, A5: Micro-basin ditches, A6: Vegetation in ditches, A7: Underground cisterns, groundwater well and recharge system, B1: Terraces on slopes, B2: Contour barriers, B3: Ditches on slopes, B4: Shrubs/trees windbreaks, B5: Natural fertilizer or animal manure, B6: Legumes/cover crops, B7: Charcoal in soil, B8: Leave crop residue, B9: Contour cropping, C1: Multiple crops, C2: Fruit trees, C3: Seed banks (resilient varieties), C4: Intercropping legumes, C5: Natural pesticides, D1: Workshops/trainings, D2: Transmission of traditional knowledge, D3: Farmers and cooperatives/associations, D4: Seed and knowledge exchange networks.

Table 1. Implemented strategies and classification based on the perception of effectiveness.

Group	Strategy	Primary benefit	Perceived effectiveness
Water management	Installing rooftop rainwater collection systems	Reduces dependence on external sources of potable and irrigation water.	High
	Constructing channels to direct water to storage tanks	Improves water management and reduces runoff loss.	Very low
	Modifying terrain for water retention	Increases the infiltration and availability of water for crops.	Very low
	Identifying low-risk areas to flooding or drought	Minimizes risk of crop loss due to extreme weather events.	Very low
	Digging trenches to direct water to micro-watersheds	Improves rainwater infiltration and utilization.	Low
	Planting vegetation in ditches	Reduces wind erosion and preserves soil moisture.	Low
	Constructing groundwater wells, recharged systems, or underground cisterns	Replenishes aquifers, reduces overexploitation and ensures water availability during dry season.	Medium
Soil conservation	Building terraces on sloped land	Prevents soil erosion and improves water retention.	Very low
	Implementing contour barriers in the plot	Reduces soil erosion and water loss, promotes sediment deposition.	Medium
	Constructing ditches on slopes	Reduces hydric erosion and preserves soil moisture.	Very low
	Planting trees (including fruit) or shrubs around cultivation areas as windbreaks	Shields crops from wind and reduces evaporation of soil moisture.	Very high
	Preparing and using natural fertilizers or animal manure	Reduces reliance on chemical inputs and promotes sustainability.	Very high
	Planting legumes or cover crops during fallow periods	Improves soil fertility and reduces erosion.	Very high
	Applying biochar to soil	Increases drought resilience and nutrient retention.	Low
	Leaving crop residue for soil protection	Reduces water loss and preserves soil moisture.	High
Crop diversification and protection	Practicing polyculture or establishing multiple crops	Diversifies income sources and optimizes land use.	Low
	Establishing seed bank of resilient varieties	Preserves agrobiodiversity, ensuring availability of seeds adapted to local conditions.	Medium
	Planting intercropping legumes	Enhances soil fertility by natural fixation of nitrogen, improving crop productivity.	Medium
	Preparing and using natural pesticides	Provides ecological pest control and minimizes environmental impact.	Very high
	Developing additional source of income	Diversifies the household economy and reduces dependence on a single income source.	Medium
Knowledge, organization, and	Modifying daily fieldwork schedules	Reduces exposure to extreme temperatures.	High
	Workshops for water harvesting construction and maintenance	Enhances community knowledge and agricultural practices.	Low

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Table 1 – continued from previous page

Group	Strategy	Primary benefit	Perceived effectiveness
community	Engaging in knowledge transfer of traditional farming practices	Promotes sustainability and strengthens community resilience.	Low
	Belonging to a farming cooperative or association	Improves access to technology, technical assistance, and markets.	High
	Participating in seed and knowledge exchange networks	Supports conservation of native crop varieties and fosters collaboration.	Very low

All participants agreed that efforts to address the challenges of climate variability and change are incomplete. In this regard, some strategies widely employed in other tropical regions, were discussed during participatory workshops. Recommended actions included improving collective decision-making, regional market integration, and social cohesion through agricultural cooperatives and more active involvement of young farmers. Reinforcing soil and water conservation practices adapted to mountainous systems; integrating water management systems (rainwater harvesting combined with drip irrigation) to enhance water use efficiency; ecosystem recovery services and diversifying livelihoods through reforestation and translocation is also required. Finally, incorporating biological control to support pest management could increase the resilience of the local productive systems.

DISCUSSION

Various authors acknowledge that climate change will affect the natural resources and ecosystem services on which the livelihoods of millions of people in rural areas depend (Altieri et al. 2020; Mertz et al. 2009; Nelson et al. 2010). Expected impacts include reduction in crop yields, emergence of new pests, migration to urban areas, and diminished seasonal employment (da Silva et al. 2020; IPCC 2022; O'Brien and Leichenko 2000). Despite efforts to address these impacts through sustainable human practices, the effects of climate change will continue to intensify (Adger et al. 2011; Belz and Wittek 2025).

The Huasteca region illustrates the vulnerability of traditional agricultural systems to climate variability and change, which is aggravated by the historical context of marginalization faced by most of the rural communities. The communities of Lejem, Tanjajnec, Xolol, and Tanchahuil in particular, face greater challenges due to high levels of poverty, limited institutional presence, and elevated exposure to environmental stressors (INEGI, 2020; Vaca-Genuit and Reyes-Hernández 2025). However, differences in social indicators among the four communities may affect their ability to respond to climate-related stressors.

The inhabitants recognize that rising temperatures, modification in rainfall patterns, and longer and more severe droughts threaten their livelihoods. These generalized conditions appear to follow similar behavior to that reported in many tropical regions around the world including Mexico. Smallholders have reported that extreme events such as droughts, erratic rainfall, and rising temperatures force them to adjust their traditional farming systems (Shrestha et al. 2022; Álvarez-Vázquez et al. 2023).

Vaca-Genuit and Reyes-Hernández (2025) have reported that droughts have expanded into the tropical region of San Luis Potosí, where the Huasteca region is located. As a result, more than 11 municipalities (including San Antonio) have registered the longest and most intense droughts in recent decades. The respondents confirmed that these adverse conditions may worsen in the future and seriously affect their livelihoods and food security given their total dependence on rainfall.

The introduction of irrigation systems can increase resilience and reduce vulnerability to drought; however, they may also increase dependence on external resources (fuel, electricity, and maintenance). For indigenous farmers, these external inputs mean additional costs and potential new vulnerabilities (Farias 2022). Newsham et al. (2018), point out that climate change adaptation strategies must consider the socioeconomic context of rural communities.

When agricultural systems are the main livelihood for thousands of households and a fundamental element of their cultural identity, they are more vulnerable to climate disturbances (Alix-García et al. 2015). Climate variability and change affect sugarcane size, increase pest infestations, reduce yields, and diminish juice quality. In responds the communities employing natural fertilizers, planting trees or shrubs around cultivation areas, participating in cooperatives, planting cover crops during fallow periods, practicing intercropping legumes and leaving crop residue for soil protection to face the climate challenges.

Tamru et al. (2025) and Trinidad et al. (2021) emphasize that technical extension services and effective knowledge transfer of sustainable land-use practices are key factors in enabling production systems to build resilience to climate risk. Our hypothesis is that training in sustainable agriculture practices through the *escuelas de campo* is facilitating the agroecological transition and reducing pressure on natural resources and production costs.

Although indigenous farmers identified ecological benefits of complex intercropping and polyculture systems, they admit that these systems require more intensive management (Molina-Anzures et al. 2016; Trinidad et al. 2021). The agroecology theory postulates that greater biodiversity enhances ecological functions and strengthens the resilience of agroecosystems to climate disturbances (Gliessman, 2021).

Worldwide communities have responded to climate impacts by adjusting their economic activities, modifying land use practices, and implementing public health initiatives to reduce heat hazards (Adger et al. 2011). In the case of the Huasteca region, these adjustments are the result of the relationship between empirical knowledge, resource availability of the farmers, and institutional support from government programs.

The integration of practices is crucial for building effective, contextualized, and enduring community-based adaptation strategies (Vaca-Pardo and Reyes-Hernández 2021). According to Altieri et al. (2020); Delgado-Serrano (2015), and Tengö et al. (2017), an effective strategy must integrate innovation, traditional knowledge, and community engagement. In contrast, limited access to technical assistance, credit, and markets inhibits the effective application of sustainable practices (Delgado-Serrano, 2015).

Some of the strategies identified in this study (widely adopted, emerging, and aspirational) were introduced by government programs, while others are rooted in the empirical experience of local actors (Figure 5). To strengthen the strategies identified as effective (Table 1), additional actions must be adopted. Some recommendations include, enhance collective decision-making, market integration, and social cohesion, through cooperatives and youth participation, integrating rainwater harvesting with efficient irrigation, promoting ecosystem recovery, and adopting biological control pest.

These proposed techniques and approaches were discussed in the participatory workshops and have been documented worldwide by Baker et al. (2020), Chartzoulakis and Bertaki (2015), Haro (2024), Pérez-Rodríguez et al. (2022), Porro et al. (2018) and Saylor et al. (2017). However, we should acknowledge that their implementation depends on institutional support.

The *Sembrando Vida* and *Producción para el Bienestar* programs, though not explicitly designed as climate adaptation initiatives, have contributed to strengthening resilience through training in agroecological practices. However, participation in these programs often require households to become involved in many activities. Moreover, inadequate agricultural inputs, limited technical assistance, and low female participation reduces their overall effectiveness (Timoteo and Sánchez 2024). In contrast, in Chiapas and Oaxaca, which are recognized as two of the poorest states in Mexico, agricultural producers have achieved better integration into these government programs (SADER 2023).

Over the past decade, the Mexican agricultural export sector has grown significantly; however, the benefits have been unevenly distributed (SADER 2021), and even some governmental programs have contradictory effects. Some studies have documented the negative effects of subsidy income transfers. For instance, Alix-García et al. (2015) found that the *Oportunidades* program increased the consumption of land-intensive goods and deforestation. Beneficiaries of the Payments for Environmental Services program only participate in conservation activities because of the subsidy (Reyes, 2023).

In the Huasteca region, some participants admit that the income from *Sembrando Vida* and *Producción para el Bienestar* programs is their primary motivation for participating in mandatory program activities. This dependency leads to an obligatory question: What will happen if these programs are discontinued or current agricultural policies change?

This study addresses the current gap in literature on climate resilience in the political context of the post-neoliberalism Mexican period. Recent policy orientations have emphasized social equity, environmental justice, and community development under a Mexican humanist political model. In a context where political transitions are focused on the most deprived and marginal sectors, it is essential to document how rural and indigenous communities adapt to climate variability and change, as well as the opportunities that arise under this new policy framework. Our research provides evidence of community-based adaptation and contributes to the broader debate on resilience and climate adaptation in agricultural systems in tropical regions.

We acknowledge that limitations in our methodology, such as the fact that most of our participants are beneficiaries of a government program, may introduce selection bias and reduce representativeness. Additionally, discontinuity in the time data could limit generalizations. Therefore, future research should include a spatial and temporal analysis of the durability of the implemented strategies and generalize them to other participants.

CONCLUSION

Erratic rainfall, rising temperatures, and prolonged droughts are the main climate changes that threaten the livelihoods, local economies, and cultural identities of the indigenous farming communities in the Sierra Citricola-Piloncillera of the Huasteca region. The implemented strategies link traditional knowledge, institutional frameworks, and resource availability of local actors. Some of the practices have been promoted by the technicians of the *Sembrando Vida* and *Producción para el Bienestar* programs, while others originate from empirical knowledge and local experience. The *escuelas de campo* seems to be an effective model for local training and reducing dependence on external inputs. Adoption of necessary yet uncommon practices essentially depends on continuous institutional support. Any change to the current agricultural policy that might occur would greatly impact the indigenous famers involved in the programs and the progress of community-based strategies. Some strategies must be consolidated to include additional techniques and approaches. Water management and the active involvement of young farmers are required. It is essential to document how rural and indigenous communities adapt to climate variability and change, as well as the opportunities that arise under a recent policy framework, where political transitions are focused on the most deprived and marginal sectors. Despite methodological limitations, the results obtained confirm the utility of qualitative approaches. Future research should prioritize spatial and temporal analyses of strategy durability and refine adaptation frameworks.

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DATA AVAILABILITY

The data that support the findings of this study are available upon reasonable request from the corresponding author.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

CONTRIBUTION STATEMENT

Carried out the fieldwork and wrote the first draft of the manuscript: HRH, CMHA.
Carried out the data analysis: ARBV, CMHA.
Wrote the first draft of the manuscript: CMHA, ARBV, HRH.
Wrote and reviewed the manuscript: ORP.
Conceived of the presented idea, supervision, review and final write of the manuscript: HRH.

DISCLOSURE OF AI USE

The authors used DeepL Write to assist with improving language clarity. The content was reviewed and edited by the authors to ensure accuracy and appropriateness.

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