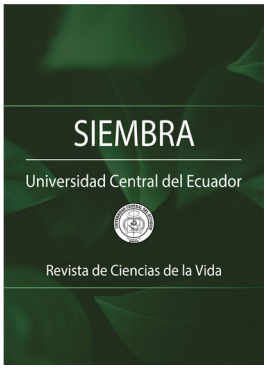
Fertilization practices in the La Compañía micro-watershed: an analysis from the perspective of agricultural producers in the State of Mexico

Prácticas de fertilización en la microcuenca La Compañía: un análisis desde la perspectiva de productores agrícolas del Estado de México



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Abstract

The process of agricultural modernization has fostered dependence on external inputs and environmental pollution. This research aimed to examine the production practices employed in traditional corn and technologically advanced potato farming systems, as well as farmers' perceptions of the socio-environmental and productive impacts of fertilizer use in the La Compañía micro-watershed, State of Mexico. The objective of this study was to identify, from the producers' perspective, the factors that influence their fertilization practices and their differential effects on local agricultural sustainability. A total of 44 semi-structured interviews were conducted with producers, and the findings reveal the coexistence of intensive, technologically advanced systems and traditional ones in the micro-watershed. While potato farmers receive private technical assistance, purchase improved seeds, and prioritize chemical fertilization, corn farmers' knowledge stems from family tradition, they practice community seed exchange, and they combine chemical and natural fertilizers. Consequently, it has been determined that a multifaceted socio-technological differentiation prevails within the micro-basin, a phenomenon that transcends conventional crop management practices. This results in the configuration of two contrasting production models, each with differentiated implications for regional agroecological sustainability.

Keywords: fertilizers, maize, potato, perceptions, agricultural sustainability.

Resumen

El proceso de modernización agrícola ha promovido la dependencia de insumos externos y contaminación del ambiente. La investigación tuvo como objetivo acercarse a las prácticas productivas empleadas en los sistemas agrícolas de maicero tradicional y papero tecnificado, así como a las percepciones de agricultores respecto a los impactos socioambientales y productivos del uso de fertilizantes en la microcuenca La Compañía, Estado de México, a fin de identificar, desde la perspectiva de los productores, los factores que condicionan sus prácticas de fertilización y sus efectos diferenciales en la sustentabilidad agrícola local. Se aplicaron 44 entrevistas semiestructuradas a productores, cuyos hallazgos

revelan la coexistencia de sistemas tecnificados intensivos y tradicionales en la microcuenca. Mientras los paperos reciben asistencia técnica privada, compran semillas mejoradas y priorizan la fertilización química; los conocimientos de los maiceros provienen de herencia familiar, practican el intercambio comunitario de semillas y combinan fertilizantes químicos con naturales. Se concluye que prevalece una compleja diferenciación sociotecnológica en la microcuenca, la cual trasciende las prácticas convencionales de manejo de cultivos, configurando dos modelos productivos contrastantes, con implicaciones diferenciadas para la sostenibilidad agroecológica regional.

Palabras clave: fertilizantes, maíz, papa, percepciones, sustentabilidad agrícola.

1. Introduction

The need to feed a growing population has led to agricultural intensification in recent decades. Over the last 60 years, the world's population has increased by approximately 4.9 billion people (United Nations Department of Economic and Social Affairs, 2024). This growth included the development of technology that promoted nutrition and, therefore, increased crop yields, thus leading to a structural process of global dependence on the use of synthetic fertilizers in agri-food production systems (Quitzow et al., 2025). Their application is essential to providing global food security (Susanti et al., 2023).

Several studies, however, highlight the inefficiency and asymmetries between countries in the use of chemical fertilizers, which has led to environmental problems, nutritional imbalances in the soil, and suboptimal food production (Penuelas et al., 2023). An example of this is the increase in fertilizer use per hectare, during the period 1966-2022, of more than 400% in regions of Africa, North America, and South America (Food and Agriculture Organization of the United Nations [FAO], 2022). This translates into an increase in application from 31 megatons in 1961 to 195 megatons recorded in 2021. Of this amount, 60% corresponds to nitrogen fertilizers (N), while the other two main types of fertilizers (phosphate and potash) account for approximately one-fifth of fertilization (Quitzow et al., 2025). This dependence is not merely technical, but it is part of an uneven geography of development, where countries in the Global South are significantly dependent on imports of fertilizers produced in the Global North.

In Mexico, this structural dependence has intensified following disruptions in global supply chains caused by the COVID-19 pandemic as well as the Russia-Ukraine conflict, which significantly raised fertilizer prices. In response to this situation, the federal government announced in 2022 plans to triple fertilizer production, with the aim of supporting local farmers and curbing consumer price inflation, achieving self-sufficiency in fertilizers by 2024 (Rentería Ximello et al., 2024). However, these initiatives reveal the magnitude of the existing dependence, and the structural limitations of the national production system, creating a scenario where national food security is intrinsically linked to the ability to access synthetic fertilizers. In fact, of the 32.1 million hectares of cultivated land nationwide, 66.8% is fertilized (Instituto Nacional de Estadística y Geografía [INEGI], 2023), showing the high dependence of the national agricultural sector on external inputs (U.S. Commercial Service, 2023). According to Duhalt (2022), the increase in fertilizer prices could mean higher costs for producing crops and/or force farmers to reduce fertilization, which could be reflected in crop yields and even in the area under cultivation, particularly among the most vulnerable farmers.

In this sense, farmers' decisions on fertilizer use can be understood as responses conditioned by institutional frameworks and agricultural policies that shape the range of possibilities for rural producers. The role of agricultural policies in farmers' decision-making on fertilizers is manifested through multiple mechanisms: direct subsidies, technical assistance programs, preferential credit, and environmental regulations (Rentería Ximello et al., 2024).

The search for technological alternatives has led to the development of fertilizers that also have the potential to improve plant growth, provide disease resistance, and contribute to sustainable agricultural practices (Zhao et al., 2024). Nevertheless, the transition to more sustainable agricultural practices requires transformations that go beyond the mere technical substitution of inputs, demanding changes in knowledge systems, access to technical assistance, marketing channels, and public policies to support the sector (Niggli et al., 2023). In this context, the study of fertilization practices in the La Compañía micro-watershed presents an opportunity to understand the specific territorial manifestations of these processes, by analyzing how farmers' production decisions, agricultural policies, and socio-environmental impacts are articulated in a specific geographical space, therefore contributing to the construction of more sustainable and socially just alternatives for rural

development.

The objective of this research was to analyze, through semi-structured interviews, the production practices used in traditional corn and technified potato farming systems, as well as farmers' perceptions of the socio-environmental and productive impacts of fertilizer use in the La Compañía micro-watershed in the State of Mexico, in order to identify, from the producers' perspective, the factors that condition their fertilization practices and their differential effects on local agricultural sustainability. The questions that guided the research were: 1. How do traditional corn and potato producers perceive the environmental and productive impacts of their fertilization practices in the La Compañía micro-watershed? 2. What differences exist in environmental perceptions between producers using the traditional corn system and those using the technified potato system, and how do these influence their fertilizer management strategies? Answering these questions provides valuable information for better understanding producers' decisions in the context of their production systems.

2. Literature review

The contemporary scientific debate on fertilizers reveals fundamental tensions between productive needs and environmental sustainability. While Penuelas et al. (2023) argue that inefficiency and asymmetries between countries in fertilizer use have led to environmental problems, soil nutrient imbalances, and suboptimal food production, Aryal et al. (2021) recognize that nitrogen fertilizers, although one of the most essential inputs for increasing agricultural production, are the main cause of nitrous oxide emissions. This duality is present in the reflections of Jwaideh et al. (2022), who point out that there is a need to increase fertilization rates in sub-Saharan Africa from 10 to 50 kg ha-1 to ensure food security. However, they warn that the intensive application of nitrogen and phosphorus fertilizers has caused eutrophication, with the enrichment of nutrients in water bodies, leading to excessive algae growth. This contradiction underscores the complexity of balancing production demands with planetary ecological limits (Steffen et al., 2015).

An emerging consensus among authors focuses on the systematic inefficiencies of current fertilization systems. Martínez-Dalmau et al. (2021) document that almost half of the nitrogen fertilizer applied is not used by crops and is lost to the environment via gas emissions or contamination of water bodies, a perspective that converges with the findings of those who report that between 50% and 70% of nitrogen (Zeng et al., 2021), and more than 70% of the phosphorus applied to the soil is lost before human consumption as food (Bouwman et al., 2013). These losses, according to Suchkov et al. (2022), result in increased crop production costs, as well as air and water pollution, thus creating a scenario where inefficiency generates simultaneous economic and environmental impacts. Lyu et al. (2021) complement this perspective by showing that the use of nitrogen fertilizers in agriculture produces significant amounts of nitrogen gases, including ammonia, nitric oxide, and nitrous oxide, therefore suggesting that inefficiencies not only represent economic losses but also direct contributions to global climate change.

Aryal et al. (2021) demonstrate that economic factors (such as access to credit and wealth) and social capital factors (such as participation in community groups and access to technical information networks) are positively correlated with increased use of inorganic fertilizers, while Touch et al. (2024) argue that smallholder farmers often lack access to modern agricultural technologies, such as irrigation systems and smart fertilization methods. This social perspective is echoed in Sánchez's (2002) analysis of global disparities in access to fertilizers, particularly in sub-Saharan Africa. However, there is a tension between the technical recommendations to increase fertilizer use to improve productivity and the warnings pointed out by Anas et al. (2020) about the excessive and inefficient use of nitrogen fertilizer, which increases pollution. This contradiction suggests that solutions require differentiated approaches according to specific socio-territorial and climatic conditions, rather than universal recipes for intensification.

The Environmental Protection Agency (EPA, 2025) documents that nutrients in fertilizers and livestock manure, pesticides, and other substances do not always remain stationary in the landscape where they are applied. This perspective aligns with the findings of Stackpoole et al. (2025) on how runoff and infiltration transport these pollutants into local streams, rivers, and groundwater. Xia et al. (2020) further develop this perspective by identifying that nitrogen and phosphorus from agricultural runoff are the main sources of nutrient input into water systems, while Guignard et al. (2017) warn that these elements can limit the growth of primary producers in most of the world's aquatic and terrestrial ecosystems. This convergence suggests that the impacts of fertilizers constitute territorial problems that require management not just at the farm level, but

also at the watershed scale,

The debate on sustainability reveals both significant convergences and divergences. Pretty (2008) argues that agricultural sustainability should promote technologies and practices that do not generate adverse effects on environmental goods and ecosystem services, while remaining accessible and appropriate to specific social and territorial conditions. This perspective is supported by Gomiero (2016), who warns that soil degradation constitutes a major threat to food security. However, tension emerges between optimistic visions of sustainable intensification and more critical warnings regarding ecological limits. Whereas Yousaf et al. (2017) document that agricultural system responses to fertilization vary considerably according to local edaphoclimatic conditions, suggesting opportunities for technological optimization, Jwaideh et al. (2022) and Pan et al. (2022) report systematic impacts that transcend local specificities. This divergence indicates that sustainability requires deeper structural transformations that go beyond technical adjustments, including changes in the socio-territorial relations that shape contemporary agricultural systems.

3. Materials and Methods

The La Compañía micro-watershed takes its name from the hydrometric station with code 18462, which was identified through the National Surface Water Data Bank [BANDAS]. The micro-watershed is located in central Mexico, between the states of Mexico and Michoacán (with 99% and 1% of the surface area, respectively). It covers an area of 290 km², encompassing the municipalities of San José del Rincón (88%), San Felipe del Progreso (6%), and Villa Victoria (5%) in the State of Mexico (Figure 1). According to INEGI (2020), the total population of the La Compañía micro-watershed registered in the 2020 Population and Housing Census was 61,376 inhabitants, of whom 51% are women and 49% are men. Of the total population, 42% live in urban areas, and 58% in rural areas, distributed across 81 localities. The economically active population corresponds to 71%, of which 29% are women and 71% are men. According to the Agricultural Frontier Series IV, the agricultural area of the basin is 168 km², corresponding to 58% of its territory. Rain fed agriculture is practiced on an area equivalent to 86% of the micro-watershed's territory, corresponding to the municipality of San José del Rincón and, to a lesser extent, to the municipalities of Villa Victoria and San Felipe del Progreso (Servicio de Información Agroalimentaria y Pesquera [SIAP], 2022).

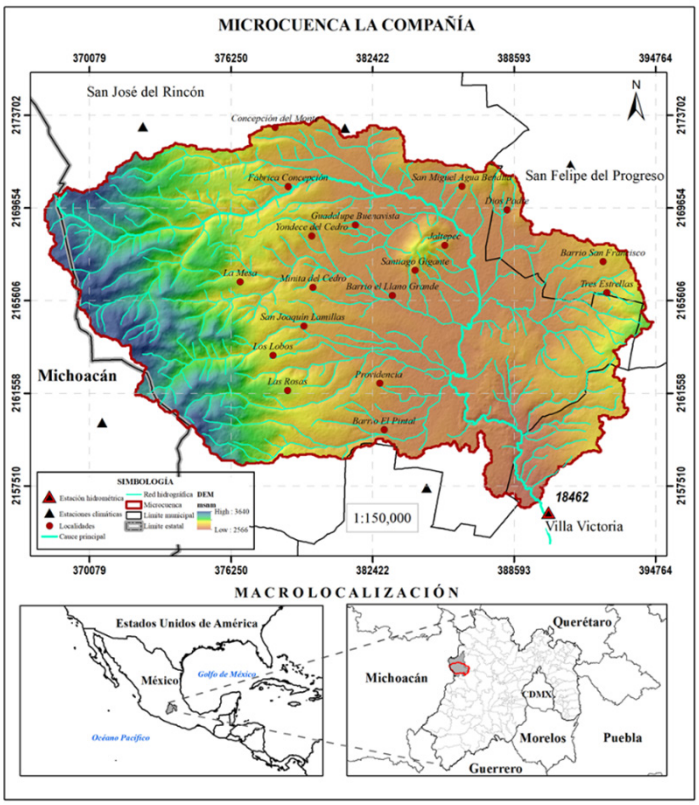

Figure 1. Location of the La Compañía micro-watershed.

From a methodological standpoint, the research adopted a qualitative approach aimed at understanding the significance that agricultural producers in the La Compañía micro-watershed, in the State of Mexico, attach to fertilizer management in their potato and corn crops. To gather the information, a semi-structured interview instrument was designed and administered to 44 farmers in the region between the spring of 2024 and 2025, with a script that explored the following topics: 1) socioeconomic characteristics (age, gender, education, land tenure, cultivated area); 2) production systems and agricultural practices (type and quantity of fertilizers, crop yields, origin of seeds, origin of fertilizers); 3) knowledge (source of knowledge for plot management); 4) environmental perception (relationship between fertilizers and pollution, environmental sensitivity, crop productivity). Additionally, all participants were informed about the objectives of the research, the use that would be made of the information collected, and their right to withdraw from the study at any time.

The sampling used was non-probabilistic, intentional, with the selection of key informants. Its objective was not to make statistical inferences, with generalizations of results for the entire population, but rather to obtain detailed knowledge about the perceptions of agricultural producers. In this type of sampling, individuals are selected based on their ability to provide information, due to their experiential knowledge of the subject under study. The sample size is based on saturation, i.e., when additional interviews no longer provide new information, since what is decisive is not the number of people interviewed, but the richness and diversity of the information provided by participants (Martínez-Salgado, 2022). The data were analyzed using Microsoft Excel, a spreadsheet application that helps organize and analyze information.

4. Results and Discussion

4.1. Socioeconomic characteristics of the people interviewed

The analysis of socioeconomic characteristics reveals determining factors that differentially condition fertilization practices between the traditional corn farming system and the technified potato farming system. The production systems of the people interviewed focus mainly on planting potatoes, or corn. The demographic composition shows a male predominance (73% men), with an age concentration within the 29-75 age group. The average age of potato farmers is lower than that of corn farmers; in fact, while the former group includes individuals between the ages of 29 and 58, the latter ranges from 34 to 75.

Women represented 27% of those interviewed, all of whom were widows with an average age of 44, who gained access to the land as successors to their deceased husbands. Previously, they were engaged in non-agricultural work, dividing their time between paid domestic employment and caregiving activities within their homes. For them, taking over the plots has meant significant challenges, including social and cultural obstacles, given that land ownership remains tied to ancestral customs, which maintain its significance as an eminently masculine resource, despite modifications to the Ejido Law in 1971, meant to grant the same agrarian rights to both men and women.

The interviewees establish a differentiated role with the plots according to the production system. In the corn system, women mainly participate in decision-making regarding organic fertilizer management, and native seed conservation. Their knowledge is strongly based on family heritage and personal experience, contributing to the preservation of traditional ancestral practices. On the other hand, in the potato system, women's participation is more focused on administrative and commercial aspects, with less direct involvement in technical fertilization decisions, which are delegated to specialized technical advisors. In fact, the trend of agricultural land management that had been developed by men (their husbands) continues.

Educational distribution is heterogeneous (25% primary, 22.7% secondary, 20.5% high school, 22.7% bachelor's degree, 4.5% postgraduate), and it significantly conditions the differential adoption of fertilization practices among the identified production systems. The level of education is significantly higher among potato producers than among corn producers. In fact, more than 63% of corn farmers have primary and secondary education, while a high percentage of potato farmers (47%) have completed high school, and even hold a bachelor's degree. This shapes contrasting patterns between the intensive use of chemical fertilizers among potato farmers and traditional practices based on organic fertilizers in the corn farming system. This educational differentiation may also influence perceptions of socio-environmental impacts, with more educated producers articulating specific issues such as soil and water pollution from agrochemicals, while those with lower levels of education prioritizing immediate impacts, such as reduced yields and water scarcity.

Land tenure structures reveal critical factors that influence the choice of production systems and associated fertilization practices. Land concentration (50% own more than 4 ha, 20% control more than 20 ha) determines that producers with larger areas (average 18.7 ha) adopt the technified potato system with intensive chemical fertilization, while smallholders (average 4.2 ha) maintain the traditional corn system with organic fertilization, and compensatory economic diversification. This spatial differentiation generates contrasting socio-environmental impacts: the potato system is traditionally concentrated in the middle and lower areas of the micro-watershed, preferably on sloping land which favors crop drainage. Nonetheless, in recent years there has been growing pressure for potato farming to expand into the upper parts of the micro-watershed, thus intensifying pressure on water and soil resources in more fragile ecosystems. In contrast, the dispersed corn system maintains practices that have less impact, but are also less productive.

Agricultural land shows marked differences between production systems, with potato farmers managing considerably larger areas, averaging 18.3 ha (range 3-47), in contrast to corn farmers, who operate smaller areas, averaging 2.8 ha (range 0.5-6). This difference in production scale conditions the economic strategies adopted: 89% of corn farmers implement economic diversification, combining agriculture with grocery trading, masonry, municipal positions, paid domestic activities, and land rental as compensatory mechanisms for the lower yields obtained with organic fertilization, or without fertilization, as well as dependence on seasonal rainfall. Meanwhile, only 42% of potato farmers resort to complementary activities, focusing mainly on grocery trade and machinery rental, but maintaining agriculture as their main economic activity due to the higher profitability per unit of area provided by technified potato cultivation. This differentiation between corn and potato producers reflects contrasting adaptive strategies conditioned by the intrinsic characteristics of each production system.

Small corn producers (average 2.8 ha) maintain less intensive organic fertilization practices, which, combined with dependence on seasonal rainfall, generates reduced yields that force 89% to implement compensatory economic diversification strategies. This diversification, although necessary for their economic security, generates seasonal pressure that further limits the intensity of agricultural management, by perpetuating a cycle of low productivity. This differentiation in economic diversification conditions the perception of risks and the capacity for transition between agricultural systems, where economic dependence on the technified potato system generates greater vulnerability to fluctuations in chemical fertilizer prices, while diversification of the corn system provides greater resilience but less capitalization for productive intensification.

4.2. Production systems and agricultural practices

The most striking differences between production systems in the La Compañía micro-watershed are evident in fertilization management. While corn crops receive an average of 100 kg ha^{-1} of urea, potato crops require approximately 350 kg ha^{-1} of DAP (diammonium phosphate), in addition to complementary fertilizers such as Triple 16 and potash. This difference reflects a fertilization intensity 3.5 times higher in the potato system compared to the corn system. In terms of planting schedules at La Compañía, corn is planted in late March and April, while potatoes are planted in late May and June. In the corn system, 41% of producers supplement chemical fertilization with organic inputs (sheep manure, chicken manure, and compost), thus maintaining partial links with traditional management practices. In contrast, the potato system showed an almost exclusive dependence on specialized chemical fertilizers and agrochemical technology packages, which include fertilizers, herbicides, and pesticides specific to optimal crop development.

A critical finding revealed that 68.2% of producers have increased the doses of fertilizer applied, arguing that there is a direct relationship between the amount of fertilization and crop yield. This is causing excessive fertilization by farmers, with the environmental consequences that this entails. With regard to the amounts of fertilizer applied in the potato system, these results coincide with those found by Arce-Estrada et al. (2025), who observed in their research, carried out in the municipality of Tlaltizapán de Zapata, Morelos, Mexico, that farmers choose to apply a higher dose of agrochemicals than recommended, believing that this increases their effectiveness. The authors echo the argument of several interviewees, who said: "You have to use more to make it work." The over application of fertilizers by farmers is directly related to a lack of adequate knowledge about their impact on environmental health; in fact, none of the farmers interviewed in the potato system associate the process of local environmental pollution with their daily soil fertilization practices.

Crop yields in the micro-watershed show significant differences between production systems. Corn yields range from 1.5 to 6 tons per hectare, with an average of approximately 3 tons per hectare, being considerably

lower in areas where beneficiaries of the government fertilizer program predominate, who report yields between 1.5 and 2.5 tons per hectare. In contrast, potato yields are substantially higher, ranging from 25 to 60 tons per hectare, with an average of around 42 tons per hectare, showing productivity up to 14 times higher than corn. This disparity reflects not only the inherent differences between the two crops, but also the intensity of technological management, where the potato system concentrates greater investment in specialized chemical fertilizers and comprehensive technology packages, while the corn system, especially in less technologically advanced areas, maintains more modest yields with greater dependence on organic fertilizers and fertilizers provided by government programs, with a widespread perception of low effectiveness.

Producers with the highest phosphorus applications (450-500 kg DAP ha^{-1}) obtain yields of 45-60 tons ha^{-1}, which, although above average, do not economically justify the additional 30-40% of fertilizer applied compared to producers who use 350 kg DAP ha-1 and obtain similar yields (40-45 tons ha-1). These application rates suggest several problematic issues: economic inefficiency, where the additional cost of fertilizer does not translate into proportional increases in yield; possible nutritional antagonism, environmental risk due to phosphorus accumulation in soils and possible leaching into water bodies; and excessive technological dependence, where producers mistakenly assume that more fertilizer equals higher yields. This highlights the need for technical assistance programs that promote balanced fertilization based on soil analysis and specific response curves to optimize both the productivity and profitability of the potato farming system.

Seed management is another extremely important factor in differentiating between corn and potato production systems. While potato producers buy improved (certified) seeds from agricultural distributors in larger urban centers, who bring them from Culiacán, corn farmers exchange their seeds directly, from farmer to farmer, saving seeds from their own harvest for the next planting season. In this way, they choose corn varieties according to the characteristics they need, knowing the performance of the plants from which their seeds came. This informal distribution system is based on traditional social alliances and family relationships, whose principles are based on interdependence and mutual trust, as well as ensuring the transmission of knowledge among peers. In the words of a corn producer:

> We get the corn seed from the corn we plant ourselves. We pick a little corn from the same ears we have, the largest and most beautiful ones are the ones we take for seed. If not, we sometimes exchange seeds with a friend or someone we have seen who has grown a good crop and must have seed, and in this case we go to see if they will sell us four or five quarts (A.G., personal communication, May 18, 2024).

Regarding the temporal evolution of agricultural yields in the La Compañía micro-watershed, the results revealed that 57% of respondents perceive a decrease in yields, contrasting with 27% who report increases and 16% who consider them stable. This distribution reflects the complexity of factors that influence local agricultural perceptions and coincides with previous studies which document the variability in producers' perceptions according to specific contexts. Similarly, different patterns are observed depending on the production system.

Potato producers who report increases in yields (mainly concentrated in localities such as Palizada, Providencia, and Las Milpas) have successfully adapted through the intensive use of specialized chemical fertilizers and technology packages. In contrast, corn producers in La Compañía, who perceive stable yields (particularly in localities such as La Peña, San Cristóbal, and some areas of Ocotillos), appear to be employing effective local strategies based on traditional organic fertilizers such as sheep manure and compost, or benefiting from specific favorable microclimates in the micro-watershed, which allows them to maintain a certain level of production stability despite the technological and nutritional limitations identified in this system.

Although corn producers combine chemical and organic fertilizers, there is a more or less widespread perception among those interviewed that the use of agrochemicals on their plots is essential in order to obtain an acceptable crop yield. Farmers' decisions regarding their preference for chemical fertilizers are embedded in a belief system that has been developing since the middle of the last century, aimed at changing the agricultural production model and creating industrialized, technified agriculture that is highly dependent on inputs. This historical process of incorporation into the technified agricultural model was called the "Green Revolution" (Chilón Camacho, 2017). As a result, fertilizers have become indispensable agricultural inputs for high crop yields, especially for cereal crops. However, geographical conditions, the capacity of crops and soil to assimilate these nutrients, and, even more importantly, inadequate land use practices have been factors that generate pollution problems and changes in the water regime. (Mateo-Sagasta et al., 2018).

In addition, a significant social impact resulting from the incorporation of farmers into the agro-indus-

trial model is the erosion and loss of knowledge that had been passed down through generations. By relying on agricultural inputs external to their production systems, they no longer draw on the experiences of previous generations who practiced autonomous agriculture. The Green Revolution created an agricultural culture embedded in an economic logic that normalized and legitimized the use of agrochemicals as a seemingly more convenient, but undoubtedly more dangerous, alternative (Arce-Estrada et al., 2025).

The principles underpinning the Green Revolution have been the subject of critical questioning for decades. While it contributed to an increase in global agricultural production, its impacts were deeply ambivalent: it failed to resolve food insecurity or eradicate famine, problems that persist due to structural issues of access, distribution, and poverty. At the same time, it generated significant negative externalities, including soil degradation, water pollution, and biodiversity loss, as well as deepening socioeconomic inequalities among farmers, excluding small producers who could not afford the required technological inputs.

However, the need for sustainable agricultural development is not yet sufficiently established in the collective imagination of farmers, and the perception remains that the application of large quantities of agrochemicals is essential to guarantee the harvest.

In this regard, a differentiated perception of the results of fertilizer application is beginning to emerge in some sectors of the micro-watershed. While potato farmers claim that commercial chemical fertilizers are effective in promoting yield increases, several farmers (both corn and potato) acknowledge a growing dependence, mentioning that "they have had to increase the amount" and that fertilizers were not even required before. In addition, some interviewees express concerns about "soil contamination" and "soil deterioration," although this perception is not widespread throughout the micro-watershed.

On the other hand, 75% of potato producers reported the need to increase or maintain applications to maintain production levels, evidencing a technological treadmill widely documented in intensive agricultural systems (Hansen, 2019). This spiral, based on technological improvement, reduced production costs, and increased farm size, explains the growing concentration of land in the hands of a small number of producers, given that those who do not join the spiral suffer from price pressure, and the most successful expand at their expense.

Particularly noteworthy is the extremely negative perception expressed by corn farmers toward the fertilizers distributed by the government program Fertilizers for Well-being. Beneficiary producers expressed systematic distrust of these inputs, with assertions about their ineffectiveness, in stark contrast to their expectations of commercial fertilizers. In addition, they report a lack of technical support and follow-up on the implementation of the actions. This perception suggests structural problems in the program's execution, which require additional research on input quality, adaptation to local conditions, and the complexity of maintaining consistency between planning and implementation in the field (Fomati Usman et al., 2025).

> This program was first called PROCAMPO, but there were still engineers and offices, but that was all. They only notified us when a check had been issued to buy fertilizer, but they never said they were going to check how we were planting. What they did say was: you have to plant, and if you don't use the fertilizer, we'll charge you for what we gave you or cancel your support. But even so, they never came, they didn't come to check whether we had planted or not. Many people preferred to sell the fertilizer they were given. (C.R., personal communication, May 18, 2024).

While Fertilizers for Well-being packages are viewed by interviewees as a negative experience, organic fertilization, particularly sheep manure, is widely accepted and valued as an excellent alternative. Corn producers consider it a guarantee of effectiveness, although they recognize limitations in availability. This favorable perception of organic inputs represents an opportunity for agroecological transition systems, consistent with global evidence on producers' preferences for sustainable practices when they prove effective (Zha et al., 2024). In contrast, various potato producers agreed that it is not possible to use organic fertilizer in cultivation because this type of fertilizer deteriorates product quality through the proliferation of fungi. However, the use of certain organic fertilizers for the prevention of diseases and pests in potato crops has been documented. (Marpaung et al., 2023).

> "Crop yields here depend on the slurry that is applied or irrigated; that is when we see yields. But if we don't apply it, there won't be any. We have noticed this for many years; slurry is needed in the soil to get better yields. That is why we already know that organic fertilizer or slurry is good" (L.E., personal

communication, May 18, 2024).

Another relevant topic addressed in the research is the origin of agricultural knowledge among the people interviewed. The findings in this area allow us to affirm that among the interviewees there are two primary sources of access to knowledge: family inheritance and access to technical advice. These sources play a crucial role in the selection of the fertilization model to be followed. In this sense, family inheritance, present in 68% of cases, generates conservative perceptions towards technological changes, while access to technical advice promotes more open perceptions towards innovations, the latter being particularly evident among potato producers. However, it should be noted that this duality reflects the unequal access to technical advice among corn producers. Many farmers face difficulties in accessing these services due to economic constraints (Morugán-Coronado et al., 2024). Meanwhile, personal experience as a source of knowledge develops pragmatic perceptions based on direct observation of results. Producers who combine multiple sources of knowledge demonstrate more flexible and adaptive perceptions, suggesting the importance of integrated approaches in agricultural extension.

In summary, agricultural production systems in the La Compañía micro-watershed reveal marked technological and socio-productive differences that transcend simple crop management practices. The potato production system is characterized by high technological intensification, dependence on specialized chemical fertilizers, access to technical advice and commercial guidance, achieving exceptional yields but raising concerns about economic and environmental sustainability due to the overuse of inputs and growing dependence on the technological treadmill. In contrast, the corn production system maintains closer links with traditional practices, integrates organic fertilizers and informal seed exchange systems, although it faces yield constraints due to nutritional deficiencies and restricted access to technical advice.

The systems show contrasting trajectories: while the corn system faces a gradual erosion of traditional knowledge inherited from generations and a growing dependence on chemical fertilizers, the potato system has been characterized since its establishment by a structural dependence on specialized chemical inputs and external technical advice. This complex configuration, where modern intensification strategies coexist with remnants of traditional management practices, highlights the need for integrated approaches that promote productive, economic, and environmental sustainability in the micro-watershed. The differentiated participation of widowed women in both systems, as well as the different sources of agricultural knowledge (family inheritance versus technical advice), reveal social inequalities that must be addressed in order to achieve greater sustainability in the Mexican countryside.

4.3. Environmental perceptions

Producers have a limited and fragmented perception of the environmental impact of their fertilizers. Most do not make a direct connection between the use of chemical fertilizers and environmental pollution, focusing mainly on the productive benefits that these inputs provide them. Nevertheless, some do express specific environmental concerns, such as soil contamination, river pollution from improperly disposed fertilizer containers, and general soil deterioration, which requires more and more fertilizer to maintain yields. Paradoxically, while some recognize that "the soil is not what it used to be", and that more fertilizer needs to be applied to achieve the same results, the causal relationship between the intensification of agrochemical use and environmental degradation is not fully understood by most people, who tend to attribute environmental problems mainly to climatic factors such as drought and changing rainfall patterns, rather than to their own fertilization practices.

The impacts on aquatic ecosystems from the entry of large amounts of fertilizers are not socially neutral, but are distributed unevenly across the territory, particularly affecting rural communities that depend directly on natural resources for their livelihoods. Synthetic fertilizers have greatly increased crop production, allowing farmers to grow more food on less land (Kumar Bhatt et al., 2019), but this increase in fertilizer use has had a significant environmental cost, particularly in terms of water quality.

Traditional corn producers expressed greater awareness of local environmental problems, with 95% identifying at least one problem (mainly water scarcity: 34.1%, and soil erosion: 13.6%), linking their perceptions to direct observation of long-term changes in their land. Notably, they reported severe erosion specifically associated with potato cultivation on slopes, recognizing the direct impact of intensive practices outside their system. In contrast, potato producers showed less sensitivity to environmental problems, with 18.2% perceiving no problems in the region.

A minority of producers establish complex causal relationships in their environmental perceptions, differentiating between external causes (climatic factors), productive causes (specific practices such as cultivation on slopes), and systemic causes (global climate change). Although not widespread, this sophistication in perceptions of causality demonstrates the existence of local environmental knowledge that could be effectively integrated into adaptive management strategies, especially if its dissemination among other producers is promoted. Significantly, 25% of producers in the potato system reported not perceiving environmental problems in the region, in contrast to the greater environmental sensitivity evidenced by corn producers. This difference in environmental perceptions between production systems suggests a need for differentiated approaches in environmental awareness programs that consider the particularities of each system.

On the other hand, the producers interviewed demonstrate a clear perception of water vulnerability, evidenced in strategies to diversify water sources. Springs are perceived as the most reliable sources, although there is growing concern about their decline. This perception is consistent with hydrological data documenting reduced water availability in the region. The dominant perception of increasing scarcity is manifested in recurring expressions about changes in precipitation patterns. This awareness of climate variability represents valuable local knowledge for adaptation strategies, coinciding with literature that recognizes producers as privileged observers of climate change. Women producers (27% of the total) demonstrated distinctive perceptions, characterized by a greater orientation toward sustainability and a community focus. All the women interviewed (100%) mentioned the importance of group training, 80% reported using compost, and all emphasized economic constraints on the purchase of inputs as a determining factor in their production decisions. These differences are consistent with literature documenting more holistic and integrated approaches among women producers (Fertő & Bojnec, 2024).

The greater propensity of women producers toward organic fertilizers and sustainable practices suggests their potential as agents of agroecological transition. However, their perceptions also reveal greater economic vulnerability, indicating the need for policies that recognize these differences in the design of agricultural programs. The role of community solidarity and shared knowledge is crucial in the development of effective adaptation strategies that can mitigate the impacts of climate change on productivity (Tassigui Sio et al., 2020).

Table 1 summarizes the analytical structure used to systematize the information obtained through semi-structured interviews with agricultural producers in the La Compañía micro-watershed. The main thematic dimensions that guided both the data collection and its subsequent analysis are broken down, and organized into specific categories that allow for an understanding of the phenomenon studied. The thematic dimensions were constructed based on research objectives and the previous theoretical review, ranging from the socio-productive characteristics of farmers to their environmental perceptions, and management strategies. Each dimension is broken down into specific variables, which, in turn, are categorized according to the patterns identified in the producers' testimonies, thus facilitating the identification of typologies and the comparison between different farmer profiles.

Table 1. Categorization and systematization of research variables.

Variable	Categories	Production System	
		Potato	Corn
Producer profile	Age range	Between 29 and 58 years old	Between 34 and 75 years old
	Gender	Mostly men, few widowed women	Mostly men, few widowed women
	Education	Predominantly middle and upper-middle education	Mainly basic and secondary education
	Cultivated area	Range of 3-47 ha (average 18 ha)	Range of 0.5-6 ha (average 2.8 ha)
	Type of fertilization	Mainly chemical, with a tendency towards intensification	Combination of chemical and organic
	Seed origin	Purchase from agricultural distributors	Seed exchange among producers
Plot management strategies	Fertilizer origin	Direct private purchase	Beneficiaries of 'Fertilizers for Well-being' and private direct purchase
	Yield	Between 25 and 60 t ha^{-1}	Between 1.5 and 6 tons ha^{-1}

Variable	Categories	Production System	
		Potato	Corn
Knowledge	Source of knowledge	With access to private technical advice	Family inheritance and community exchange
Environmental perception	Fertilizer-contamination relationship	No perceived relationship between pollution and fertilization	A relationship is perceived between pollution and fertilization, and potato farmers are blamed
	Environmental sensitivity	Low sensitivity to environmental issues	High sensitivity to environmental issues, citing causal relationships
	Changes in productivity	Increased productivity with chemical fertilization and technological packages	Stable yields with a tendency toward reduced productivity

5. Conclusions

Analysis of corn and potato production systems in the La Compañía micro-watershed reveals complex socio-technological differentiation that transcends conventional crop management practices, resulting in two contrasting production models with different implications for regional agroecological sustainability. The results show marked stratification between potato and corn producers, determined by structural socioeconomic factors. Potato producers, characterized by higher levels of education, extensive agricultural areas, and access to specialized technical advice, have adopted a model of technological intensification that generates high yields (average of 42 tons ha-1) through the application of specialized chemical fertilizers, comparable to national standards of technified production. In contrast, corn producers, with lower levels of education, smaller production areas, and dependence on inherited knowledge, maintain traditional production systems with modest yields, but integrated with organic fertilization practices and compensatory economic diversification.

The differences identified between the two production systems reveal that the traditional corn system maintains greater diversity of practices, less dependence on external inputs, and greater integration of local knowledge. In contrast, the technified potato system, despite its higher productivity, shows vulnerabilities associated with chemical dependence, accelerated soil degradation, and lower resilience to environmental disturbances.

The research documents a process of progressive chemical intensification, particularly pronounced in the potato system, where producers have increased the doses of fertilizers applied, reaching very high levels of DAP that exceed official technical recommendations. This dynamic creates a technological treadmill where 75% of potato producers report a need to increase applications to maintain production levels, highlighting a growing dependence that compromises the economic and environmental sustainability of the system. The over application of phosphorus does not translate into proportional increases in yield, therefore suggesting economic inefficiencies and environmental risks due to nutrient accumulation.

The corn farming system maintains significant links with traditional practices, using organic fertilizers (sheep manure, chicken manure, compost) and developing informal seed exchange systems based on social relationships of mutual trust. This persistence of traditional knowledge, transmitted mainly through family inheritance, represents a valuable agroecological heritage that coexists with pressure toward chemical intensification, although it faces limitations due to nutritional deficiencies that explain suboptimal yields.

Producers demonstrate varying levels of environmental awareness, with corn farmers showing greater sensitivity to local environmental problems, such as water scarcity and soil erosion, derived from direct observation of long-term changes in their land. In contrast, a significant percentage of potato farmers do not perceive environmental problems. Women producers, mainly widows who have inherited land, demonstrate different patterns of participation depending on the production system. In the corn system, they actively participate in decisions about organic fertilization and the conservation of native seeds, contributing to the preservation of ancestral practices. In the potato system, their participation is concentrated in administrative and commercial aspects, delegating technical decisions about fertilization to specialized advisors, maintaining previously established management patterns.

The findings reveal a marked differentiation between intensive technified and traditional systems in the micro-watershed, with little interaction between potato and corn producers due to their contrasting produc-

tion logics. The positive evaluation of organic fertilizers among corn producers and the growing perception of chemical dependency represent opportunities for sustainable transition programs. However, the inequality of access to technical advice, the pressure of the technological treadmill, and the gradual erosion of traditional knowledge constitute structural obstacles that require comprehensive interventions. The present research shows that agroecological sustainability in the La Compañía micro-watershed requires integrated strategies recognizing the sociotechnical specificities of each production system, promoting the co-evolution of traditional knowledge and appropriating innovations, and which address differences in gender and resource influencing fertilization practices, as well as the environmental perceptions of agricultural producers.

The results suggest the need for differentiated agricultural policies that recognize the identified socio-technological heterogeneity. For the potato system, nutritional optimization programs based on alternative fertilization, as well as agronomic management that reduces soil degradation and, at the same time, decreases the amount of fertilizer applied, are required. For corn, it is essential to strengthen extension systems that integrate traditional knowledge with appropriate agroecological innovations, improving equitable access to technical advice without compromising productive autonomy.

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Contributor roles

- Aurora Guadalupe Martínez-Ponce: conceptualization, investigation, methodology, resources, writing – original draft.
- Luis Ricardo Manzano-Solís: supervision, investigation, software, writing – original draft.
- Denise Soares-Moraes: validation, writing – original draft, writing – review & editing.
- Roberto Franco-Plata: writing – review & editing.

Ethical implications

The authors declare that prior to the administration of the semi-structured surveys, each participant voluntarily gave their informed consent. The confidentiality of personal data and the anonymity of the participants were guaranteed in the processing and publication of the results. Given the nature of the study, which consisted solely of conducting semi-structured interviews on fertilizer management practices without experimental intervention or risk to the participants, formal approval from an institutional ethics committee was not required.

Conflict of interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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