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Socioeconomic analysis of the use of water management technology by Mexican greenhouse tomato farmers toward sustainable production

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The UN predicts that by 2050 the world's population will have reached 9.8 billion people, posing a challenge for agriculture, which must produce enough food to feed them without harming the environment. However, agricultural production has increased with the use of technology that has harmed the environment and human health, among other factors. This indicates the need to understand the elements of the agroecosystem, as well as their functions and interactions within and outside the system, to develop a comprehensive improvement strategy leading to sustainable production. Water is scarce and also very important, so it must be used efficiently. Therefore, a socioeconomic analysis of greenhouse tomato (*Solanum lycopersicum* L.) farmers was conducted, focusing on the use of technology for water management in the municipality of Texcoco, Mexico, to identify critical points of the system, propose interventions, and train farmers towards sustainable production. A survey was conducted on farmers in their greenhouses, and a multidimensional, systemic, and transdisciplinary analysis of the agroecosystem was carried out. Principal component and cluster analysis were carried out. Based on productivity, farmers were classified into Low Yield (LY), Medium (MY), and High Yield (HY). They had yields of 192.27, 196.67 and 287.50 t ha⁻¹ with a benefit–cost ratio of 1.2, 1.5 and 3.78, respectively. Ninety percent of farmers in the LY cluster use their experience to determine how much and when to irrigate, whereas those in the HY cluster use technology or technical advice. Education, labor, productivity, subsidies and the use of technology were identified as critical points. LY and MY do not have water management technology, which affects productivity. Strategies were proposed to strengthen the knowledge of farmers and the adoption of technologies for sustainable agriculture through extension services, active and ongoing organization, financing to obtain infrastructure, machinery, and equipment, linking producers with educational, research, and government institutions, and establishing school plots. To improve the knowledge of farmers, workshops on sustainable greenhouse tomato production were held for them in Mexico and Panama, with an emphasis on water use.

KEYWORDS

farmer education, irrigation frequency, *Solanum lycopersicum* L., sustainable production, use of technology

1 Introduction

The UN (United Nations) (2024) estimates that by 2050 the world's population will reach 9.8 billion people. This represents a challenge for agriculture: producing the quantity and quality of food necessary for this growing population. The problem lies in the fact that food production requires a great deal of water, which is a limited resource. In the global context, in 2024, 3.28 billion people were affected by water scarcity [UN (United Nations), 2024]; therefore, the UN (United Nations) (2023) continues to work on water availability and management. However, the number of people affected may increase because river basin consumption exceeds recharge. It is estimated that terrestrial water storage has decreased by 27,079 billion m³ in the last 50 years (McCartney et al., 2022), influenced by climate change (Sawkar and Rajendra, 2017). On the other hand, water is the main input for food production, with more than 70% of the total consumed in the world being used for it (FAO, 2020), which puts pressure on water resources (FAO et al., 2022). In Mexico, up to 76% of the water consumed is used in agriculture, which has led to the overexploitation of underground aquifers [CONAGUA (Comisión Nacional del Agua), 2018] in the central, northern and northeastern areas of Mexico [CONAGUA (Comisión Nacional del Agua), 2019]. In the Texcoco region, 95% of the water used is extracted from groundwater (Aguilar et al., 2011), and the increase in water demand has led to a decrease in the storage of groundwater; there is a water availability deficit in the Texcoco aquifer of more than 111 million m³ [Diario Oficial de la Federación (DOF), 2020]. Therefore, as food production increases, so does water consumption, making it essential to use water in agriculture efficiently with the aid of technology.

Many countries around the world use a variety of technologies to increase water use efficiency (WUE). For example, in the United States, irrigation systems, irrigation controllers, and programmers, and fertigators with weather and soil moisture sensors are used to increase WUE (Bar-Yosef, 2008; Van Os et al., 2008; Waller and Yitayew, 2016). Another example is the use of sensors, a communication system, and a drip irrigation system in tomatoes, which managed to increase yield from 13 to 167 kg m⁻³ (Kanan et al., 2022). Another alternative to increase WUE is the use of protected agriculture, for example, with advanced technology, 4 L of water are used to produce 1 kg of tomato, whereas with basic technology, approximately 300 L are required (Salazar-Moreno et al., 2020). In 2016, there were 400,000 hectares of greenhouses worldwide, with China having the largest area (82,000 ha), and Mexico having 20,000 ha of greenhouses [Rabobank (RaboResearch Food and Agribusiness), 2018] and 25,814 ha under protected agriculture [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2016]. In Mexico, this area increased in 2021, with 47,253 ha were planted under protected agriculture, and 14,379.81 ha were in greenhouses [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2021]. Hence the need to increase the use of technology to increase WUE in developing countries compared to developed countries.

Based on the above, it can be stated that the use of technology in water management, combined with the knowledge of plant water requirements and soil or substrate characteristics, allows for the provision of water at the time and in the quantity required by the plant (Waller and Yitayew, 2016; Zepeda-Bautista et al., 2021). In this context, farmers must be aware of the need and prepared, to reduce water consumption by improving irrigation methods, techniques, and

agricultural management practices (De Pascale et al., 2017), and by receiving training in the use of technology, which must be accessible to them. However, the water problem is not only a farmer's issue but a societal one; therefore, the community must provide comprehensive solutions based on the planning, conservation, and management of water resources (Sawkar and Rajendra, 2017), starting with an understanding of agroecosystems.

In this context, it is important to ensure a responsible production and consumption [UN (United Nations), 2015] by farmers and consumers, respectively. To achieve this, it is crucial to understand the elements, their functions, and interactions, as well as the effects of environmental, political, social, economic, and technological factors within and outside the agroecosystem (Dominguez-Hernandez et al., 2022; Suazo-López et al., 2025). This involves identifying the needs of agricultural producers and their environment, followed by proposing and developing a comprehensive solution, then returning to establish intervention with producers, and finally, repeating the cycle for continuous improvement (Domínguez and Zepeda, 2024). This time, the water input is studied.

Several researchers have carried out diagnoses of the Mexican agricultural sector. For example, Dominguez-Hernandez et al. (2018) classified the farmers of the traditional maize agroecosystem in Ahuazotepec, Puebla, into three categories: low-traditional, medium-traditional, and transitional, each with different indices of economic, environmental, and social sustainability. Similarly, Flores et al. (2023), when diagnosing the prickly pear cultivation system, identified two groups of farmers facing issues such as pests and diseases, low levels of technological advancement, weak organization, and limited marketing channels, as well as the need for technical support and training. On the other hand, Ramírez-Jaspeado et al. (2023) proposed grouping maize farmers in the State of Mexico to optimize costs related to improved seeds, fertilizers, machinery acquisition, and production mobilization. Regarding greenhouse tomato cultivation, Mundo et al. (2020) found a close relationship between the technological level of the production unit, the educational level, the cultivated area and the experience with productivity in producers in Puebla, Mexico, and conclude that technical advice and training in the use of technologies should be provided to obtain homogeneous yields in the area. Meanwhile, Suazo-López et al. (2025) grouped tomato farmers from Texcoco, State of Mexico into low, medium and high technological levels in production; these use the same crop production activities but do not have the same economic, environmental, social, and technological sustainability indices. However, there are few studies carried out with producers to calculate their water use efficiency.

The analysis of horticultural production systems, particularly regarding water use efficiency, is limited and highly specific. However, it is essential in order to define the system's baseline, which in turn helps plan, design, construct, and implement interventions with a multidisciplinary, systemic, and transdisciplinary approach (Domínguez-Hernández and Zepeda-Bautista, 2025) to achieve comprehensive improvement. Therefore, a socioeconomic analysis of greenhouse tomato (*Solanum lycopersicum* L.) farmers was conducted with an emphasis on the use of technology for water management in the municipality of Texcoco, Mexico to identify critical points of the system, propose interventions, and train farmers towards sustainable production. This under the assumption that small vegetable greenhouse farmers lack the financial resources and agricultural

technical knowledge to acquire and operate water management technology, which affects their productivity negatively, compared to those farmers who do have these resources.

2 Materials and methods

To carry out this research, the Multidimensional, Systemic, and Transdisciplinary Analysis for Agricultural Research (MSTAAR) method was applied in its first three phases (Domínguez-Hernández and Zepeda-Bautista, 2025). This methodology offers an iterative framework to diagnose agroecosystems, co-design context-adapted interventions, and evaluate their impact across multiple dimensions. In this case, the study began with the definition of the research object and culminated with the design and implementation of training workshops for producers. It is important to note that while these phases are grounded in the Mexican context, they can be adapted to other countries.

To define the object of study, the literature review method described by Check and Schutt (2012) was applied. The search was conducted in scientific, dissemination, and statistical information databases at the local, national, and international levels. For the diagnosis, which involves identifying the target population, designing and applying the survey, generating a database, analyzing the information statistically, and establishing a baseline for future evaluation, the following were used: (1) the survey method for

obtaining data as described by Check and Schutt (2012), (2) multivariate statistical methods for data analysis and presentation according to Köbrich et al. (2003) and Han et al. (2012), and (3) Phase 3 (Identification of Factors Affecting Production) of the MSTAAAR described by Domínguez-Hernández and Zepeda-Bautista (2025). Finally, the workshops were designed and implemented to producers using the method proposed by Ørngreen and Levinsen (2017). These research activities are described in detail in the following sections.

2.1 Study area description

The study was conducted in the municipality of Texcoco, located between geographic coordinates 98° 39' 30" and 99° 01' 44" West and between 19° 23' 41" and 19° 33' 45" North, with an area of 422.49 km² at an altitude of 2,246 m above sea level in the East of the State of Mexico, Mexico (Gobierno del Estado de México, 2022; Figure 1). According to the Köppen classification, the climate is temperate (Cw) with summer rainfall, an average annual temperature of 16.4 °C, and an average precipitation of 618.5 mm [Servicio Meteorológico Nacional (SMN), 2024].

According to the 2020 census, Texcoco has a population of 277,562 inhabitants, of whom 51.4% are women and the rest are men, with an average age of 30 years. The population density is 648.3 inhabitants per km², and 60.8% of the population is economically active. Regarding education, 44.8 and 24.4% have basic and higher

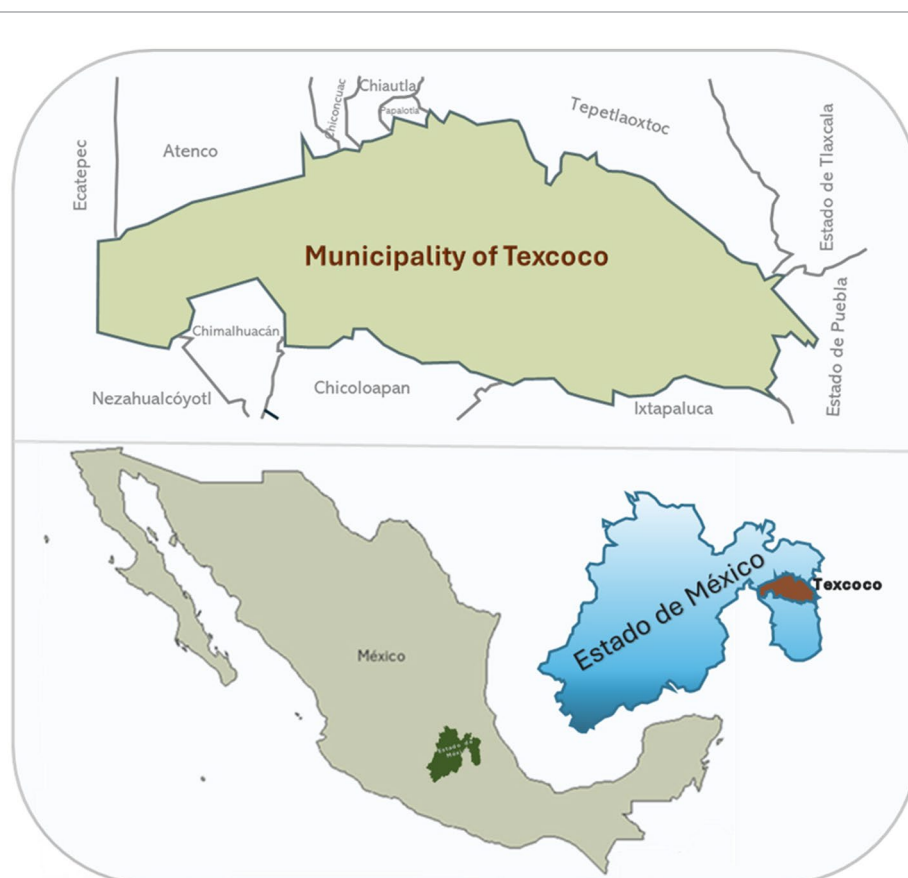


FIGURE 1
Geographic location of the municipality of Texcoco.

education levels, respectively. Additionally, 40.7% have a computer, 90% own a mobile phone, and 66% of the population is affiliated with health services (INEGI, 2023a). This information is important to show the social and economic context in which the research was carried out and the possible application of the results in other countries with similar characteristics.

Ninety-five percent of the water consumed in the Texcoco region is extracted from groundwater (Aguilar et al., 2011), and the increased demand for water has caused groundwater storage to decline. In the case of the Texcoco aquifer, the rates of decline in groundwater levels between 1968 and 2014 ranged from 0.76 to 1.31 m year⁻¹ (Carrillo et al., 2016). According to the *Diario Oficial de la Federación* (DOF) (2020), there is a water availability deficit in the Texcoco aquifer of more than 111 million m³. The issue of water availability may worsen soon, leading to a further decline in the aquifer's water table. This situation is exacerbated by the lack of water conservation campaigns and their connection to environmental care (Aguilar et al., 2011). The problem of water availability could worsen soon, given the continued population growth in Texcoco, as well as its food production, and that both factors require water. During 2021 in Texcoco, 83 hectares of greenhouses were used for both ornamental and vegetable crops. Tomato cultivation is the second most widely cultivated crop, with 26 hectares used for this purpose, producing 2,470 tons and yielding an average of 95 t ha⁻¹ [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2021].

2.2 Target population

To define the target population, the 26 hectares with greenhouse tomatoes planted in Texcoco [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2021] and the average production unit size of 329 m² (Bastida, 2017) were considered to estimate the number of producers. Subsequently, the sample size was calculated using the

equation proposed by Malhotra (2008): $n = \frac{Z^2 pqN}{NE^2 + Z^2 pq}$, where n is

the sample size to be calculated, N is the studied population, Z is the normal score, E is the estimation error, p is the probability of finding the desired characteristic in the studied population, and q is the probability of not finding the desired characteristic, meaning that $q = 1 - p$. Thus, considering $N = 790$, $Z = 1.64$, $E = 10\%$, and p and $q = 0.5$, the calculated sample size was 62 greenhouse farmers, representing 8% of the total.

2.3 Classification of tomato farmers

To group the farmers, a survey was designed with six sections: General information about the producer, greenhouse type and equipment, seedbed management, crop management, quantity and source of water used for production, and weather conditions affecting horticultural and ornamental production. The survey was designed according to the production function of the greenhouse tomato agroecosystem, which covered inputs, production activities, and the product (quality, sales, and post-harvest handling; Fioretti, 2007), as well as indicators reported by Mundo et al. (2020), Vargas-Canales et al. (2018), and Sánchez and Moreno (2017).

To conduct the survey, farmers were selected using a non-probability convenience sampling method, where the sample population is selected through a non-systematic process that does not guarantee equal opportunities for each subject in the target population. In this method, researchers enroll subjects based on their availability and accessibility (Elfil and Negida, 2017). To achieve this, the researcher contacted the known producers in person and over the telephone; the greenhouses in the municipality of Texcoco were then geographically located (Figure 1) using GPS, and finally, the survey was conducted. The inclusion criterion was that farmers must plant in greenhouses. A total of 47 surveys were conducted between May and September 2021 using the Microsoft Forms® platform and in person in the production units. A database was created using Excel® (Microsoft Corp, Redmond, WA, United States) to capture the variables obtained with the survey and close the revision of the data, which simplified the information management. While the number of greenhouse producers surveyed in Texcoco (47) could be considered small, it is important to point out that they come from the Mexican context, where the total greenhouse area is relatively low [15,330 hectares in 2024; SIAP (Servicio de Información Agroalimentaria y Pesquera), 2025] compared to developed countries such as China, which had 1.3 million hectares of greenhouse infrastructure in 2019 (Tong et al., 2024). However, this process of fieldwork to obtain information and conduct system analysis can be adapted to other countries with similar socioeconomic and agricultural conditions.

To characterize the system, a Principal Component Analysis was conducted on the survey results. Fourteen variables were evaluated, relating to greenhouse equipment, irrigation frequency in the seedbed and crop, cultivation system, nutrient solution, fruit yield, and income and expenses. The goal was to reduce the dimensionality of the system, facilitate interpretation, visualization, and understand the interactions between observations, and determine which survey variables contribute most to data variability (Han et al., 2012).

The variables were measured as follows:

1. Irrigation equipment – the number of farmers who have any irrigation equipment other than drip irrigation, such as misting or wet wall, was quantified.
2. How do you define irrigation? The farmers were asked how they determine the amount and time of each irrigation, either by experience or with the help of sensors or a technical advisor.
3. How do you program irrigation? This was defined based on what the farmer uses to apply each irrigation: manually, with an irrigation programmer or with fertigation equipment.
4. Seedbed irrigation – manually or automatically.
5. Cropping system – it can be in the soil or hydroponics.
6. Application of the nutrient solution – this can be in each irrigation, daily, weekly or monthly.
7. Measurement of pH and electrical conductivity (EC) for the control of the nutrient solution – the farmers who measure the pH, EC or both were counted.
8. Number of irrigations per day – the average number of irrigations applied by farmers per day was determined.
9. Irrigation time – the average time that farmers apply to each irrigation was determined.
10. Dripper expenditure – the average expenditure of the emitters, was calculated.

11. Volume of water applied (L) per square meter per day was calculated using data on dripper expenditure, number of irrigations and irrigation time.
12. Fruit yield per hectare – the average in tons ha⁻¹ was calculated.
13. Income – the fruit yield was multiplied by its sale price.
14. Expenses – the expenses of each input used in tomato cultivation were added and the average was subsequently calculated.

Finally, the cost–benefit ratio was determined by dividing the total revenue by the overall production costs according to Arulmani et al. (2022). Profits were calculated by subtracting total costs from revenue over the course of a production cycle, and water use efficiency was calculated by dividing the yield per hectare by the total volume of water applied (kg m⁻³) during the crop cycle as noted by Feleafel and Mirdad (2014). It is important to mention that these variables were calculated using data provided by the farmer in the survey, and were not obtained through experimentation.

The first two principal components (PC) were used in the Cluster Analysis (CA). This analysis was conducted to identify groups of tomato farmers based on the technology that they use for water management in tomato productivity in greenhouses in Texcoco. Hierarchical cluster models were created using the Euclidean distance method to determine the distance between observations and Ward's criterion to optimize the minimum variance within clusters (Köbrich et al., 2003). This analysis allows for the grouping and characterization of observations within each cluster and then obtaining the means and percentages of the studied variables (Han et al., 2012). Statistical analyses were performed using the Statistical Analysis System software [SAS (Statistical Analysis System Institute), 2014].

2.4 Identification of factors affecting production

Based on the information collected and analyzed during the agroecosystem characterization, the key critical points, both positive and negative, were identified in each component (social, economic, and technological), as mentioned by Domínguez-Hernández and Zepeda-Bautista (2025). This was done to determine which elements of the system function effectively and which require improvement. For each category, the following questions were considered: How does this factor affect the agroecosystem under study? Is it feasible to modify it? And, if so, how, when, and where should the modifications be applied? This information will be useful for designing and implementing interventions to improve the system.

In this case study, and given the conditions of greenhouse tomato producers in Texcoco, only one intervention related to producer training was designed and implemented due to limited human, financial, and infrastructure resources, as well as time constraints for research. However, several potential interventions were identified that could be designed and implemented in other sites with similar conditions.

3 Results

To classify tomato farmers in the municipality of Texcoco, Mexico, the Principal Component Analysis (PCA) showed that the first two principal components explained 44.94% of the total variability—31.23 and 13.70%, respectively. Principal Component 1 (PC1) was named *Productivity* because it includes the variables income (I) and fruit yield per hectare per year (FY), which had eigenvalues of 0.39 and 0.35, respectively. This is due to a moderate correlation ($r = 0.60$) between I and FY. On the other hand, Principal Component 2 (PC2) named *Water management in production* is made up of the cultivation system (hydroponics and soil), average irrigation and drip irrigation with weights of 0.49, 0.46, and 0.45, respectively.

Based on Principal Components 1 and 2, the Cluster Analysis classified greenhouse tomato farmers in Texcoco into three groups (Figure 2). The characteristics of these groups were obtained from the survey results database. According to the tomato yield classification proposed by Mundo-Coxca et al. (2019), the clusters were named Low Yield (LY), Medium Yield (MY), and High Yield (HY).

The social characteristics of the farmer, the technological characteristics for water management and the economical characteristics of the production units, all described in the following sections, were determined for each group.

3.1 Social characteristics of the farmer

The cluster of LY includes 33% of the farmers surveyed. Their average age is 52, and they have been dedicated to working on greenhouse production for 7 years. Around 18% of the farmers are women, and family labor is used in 55% of their production units. Regarding education, 45% of the farmers in this group have a university-level education, while 9% only completed primary school. For 73% of the producers, the income from production serves as a supplement to their earnings. No producer belongs to any organization (Table 1).

Farmers in the MY cluster (55% of the farmers surveyed) are on average 5 years younger and have dedicated more years to greenhouse production than farmers in the LY cluster (Table 1). They use family labor like the farmers of the LY cluster and have 4% more participation of women in the production process. In this cluster, 17% have postgraduate studies and the same percentage have university studies, while farmers in the LY and HY clusters do not have postgraduate studies; 33% percent of farmers in this group mentioned that income from the production unit supplements family income (Table 1), and 17% actively belong to an organization to carry out agricultural activities.

The third cluster of HY includes the youngest farmers (average age 32, 12% of the farmers surveyed) with university education, a higher percentage of women, and no family labor is used in the production unit compared to the LY and MY clusters (Table 1). Farmers have been engaged in greenhouse production for an average of 3 years, and for 50% of them, the income represents their primary source of family earnings.

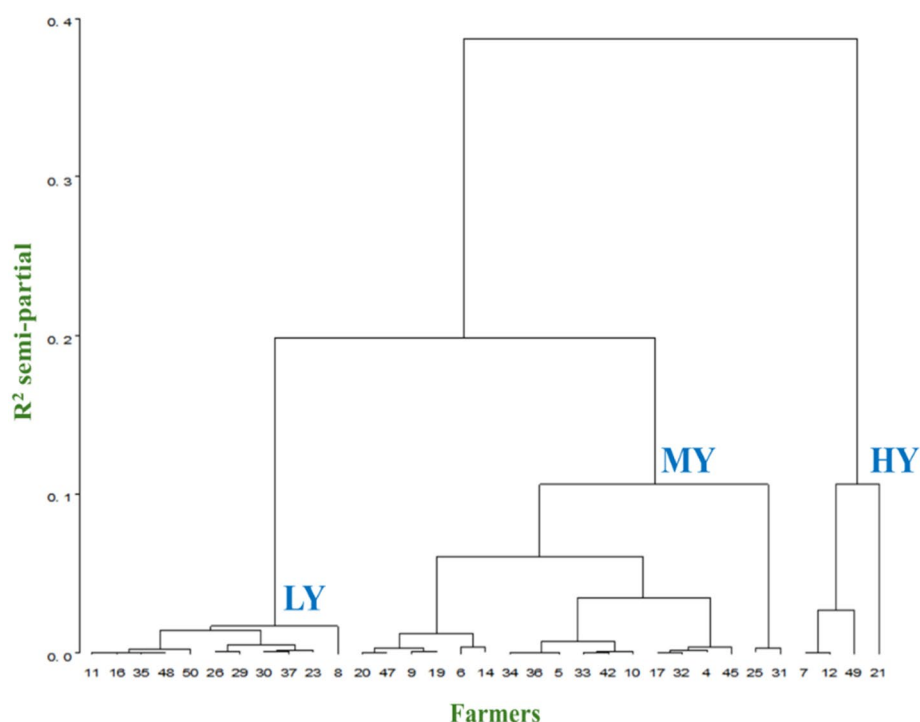


FIGURE 2

Dendrogram of the clusters generated by greenhouse tomato farmers in Texcoco. Each cluster is identified by its acronym: Low Yield (LY), Medium Yield (MY), and High Yield (HY).

TABLE 1 Social characteristics of each group of greenhouse tomato farmers in Texcoco, Mexico.

Characteristic	Tomato yield in greenhouse		
	Low	Medium	High
Family labor force (%)	55	56	0
Women (%)	18	22	50
Average age (years)	52	47	32
University studies (%)	45	17	100
Postgraduate studies (%)	0	17	0
Main source of income (%)	27	33	50
Years dedicated to horticulture	7	10	3

Although the LY and MY groups have similar yields, they use different water management technologies and require different interventions for improvement. While cluster HY has few members, it was included because it has a standardized agricultural production process; it can be replicated and considered an example for both groups (Figure 2). While this farmer classification was created in the Mexican context, it can be adapted to other countries with similar conditions.

3.2 Use of technology for water management of the production units

Figure 3 shows the behavior in the use of water management technology among the three groups of horticulturists, revealing an

increase in the number of farmers who rely on different technologies to manage water, from the LY cluster to the HY cluster. The use of fertigation systems or irrigation programmers increases from 10% in the LY cluster to 100% in the HY cluster. A similar trend is observed with the use of sensors or technical advice to determine the amount and distribution of irrigation water. In the LY group, 90% of tomato farmers determine how much and when to irrigate based on their own experience. In contrast, in the HY group, all horticulturists use technology or technical advice to determine the volume and frequency of irrigation.

Based on the measurement of nutrient solution parameters that influence the availability of macronutrients and micronutrients for the plant, such as pH and electrical conductivity (EC), the LY and MY clusters show similar behaviors in the number of farmers who measure pH and EC in the nutrient solution (36 and 33%, respectively). However, in the HY group, 100% of the farmers conduct pH and EC measurements.

The water management parameters for greenhouse tomato production in Texcoco are shown in Figure 4. The figure shows an increase in the number of irrigations from the LY cluster to the HY cluster, ranging from 1 irrigation per day in the LY cluster to 17 irrigations per day in the HY cluster. Additionally, the volume of water applied per square meter per day increases, though to a lesser extent, from 2.9 L m⁻² day⁻¹ in the LY group to 4.9 L m⁻² day⁻¹ in the HY group. In general, tomato farmers in the HY use a greater number of irrigations and consequently a larger volume of water applied in comparison to the LY and MY. Regarding water use efficiency, expressed as kilograms of tomato produced per cubic meter of water, the MY

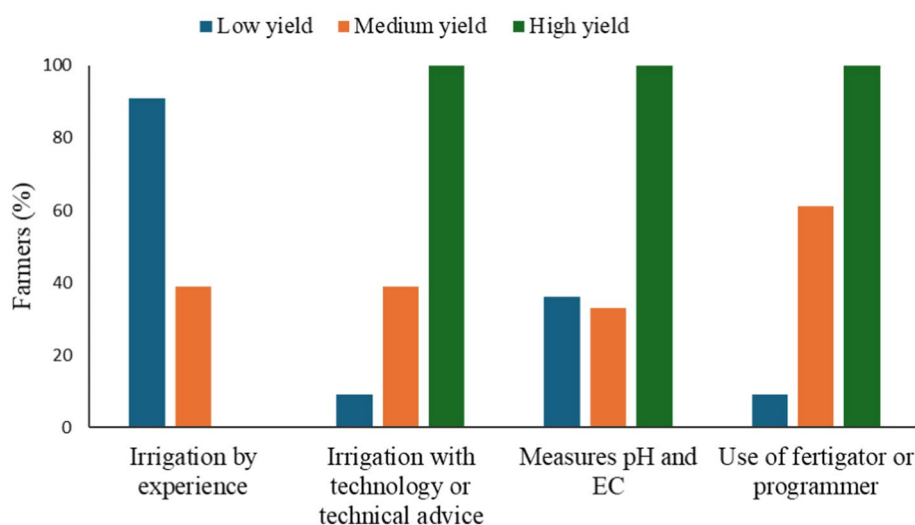


FIGURE 3

Use of technology for water management in greenhouse tomato production in Texcoco, Mexico. EC, electric conductivity.

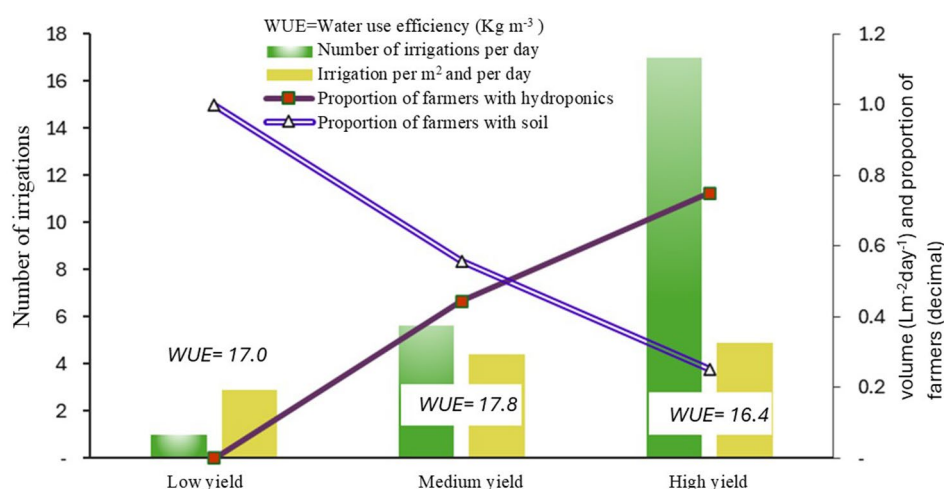


FIGURE 4

Water use efficiency and management in greenhouse tomato production in soil or hydroponics by farmers in Texcoco, Mexico.

group showed the highest value, followed by the LY group, while the HY group had the lowest. The LY and HY groups showed values 4.49 and 7.87% lower, respectively, compared to the MY group (Figure 4).

Greenhouse tomato production in Texcoco is carried out in two systems: hydroponics and soil. All farmers (100%) in group LY plant tomatoes in soil, whereas only 44 and 25% of the farmers in groups MY and HY do so; the rest use hydroponics (Figure 4). It is worth noting that 75% of the farmers in the HY group plant using hydroponics.

3.3 Economic characteristics of the production units

Regarding greenhouse size, the MY cluster has the smallest average size (1,697.22 m²) followed by the LY and HY clusters—44.55 and 593.92% larger—compared to MY, respectively (Table 2).

TABLE 2 Economic characteristics of three cluster of greenhouse tomato farmers in Texcoco, Mexico.

Characteristic	Tomato fruit yield		
	Low	Medium	High
Greenhouse area (m ²)	3,060.82	1,697.22	19,875.00
Yield (ton/ha)	192.27	196.67	287.50
Profit (Mexican pesos per hectare)	612,146.59	373,225.91	5,170,271.28
Cost–benefit ratio	1.50	1.23	3.78
Final consumer sales (%)	27	6	0
Intermediary sales (%)	73	94	0
Export sales (%)	0	0	100

On the other hand, tomato fruit yield is similar in the LY and MY clusters, while the HY cluster achieves, on average, a higher fruit yield (Table 2). Although the LY and MY clusters have similar yields, profits are 64% higher in the LY group because farmers have 20% lower production costs compared to MY and 31% lower than HY. However, the HY cluster surpasses both the MY and LY clusters, with profits exceeding 5 million Mexican pesos per hectare (Table 2). The cost-benefit ratio is also higher in the HY cluster (3.78) in comparison to the MY (1.2) and LY (1.5) clusters.

Regarding the destination of the produce, the LY group sells 27% to the final consumer and the rest to intermediaries, whereas the MY group only sells 6% to the final consumer and the rest, to intermediaries. On the other hand, the HY group sells all its production to the foreign market (export) (Table 2).

4 Discussion

The Principal Components Analysis showed that the main variables used to classify tomato farmers in the municipality of Texcoco, State of Mexico, Mexico, were related to productivity (i.e., income, which is significantly related to tomato fruit yield per hectare per year) and water management in production (i.e., hydroponic and soil cultivation, average irrigation, and drip irrigation). These variables are important for improving water use efficiency in production units. If the volume of water per kilogram of tomato fruit can be reduced from 46.6 L kg⁻¹ in open fields to 31.6 L kg⁻¹ in greenhouses using technology, greater water use efficiency can be achieved (Maureira et al., 2022). There is also a correlation between fruit yield and irrigation per day ($r = 0.51$) and between water per m² and cultivation system ($r = 0.50$). This is because there is a close relationship between the volume of water applied and the fruit production obtained, hence the importance of an efficient water use (Shewangizaw et al., 2024).

4.1 Socioeconomic and technological characteristics of production units

Tomato fruit yields obtained by farmers helped classify them into three groups. This research found that farmers belonging to the LY and MY groups have similar tomato fruit yields; while farmers in the HY group achieve, on average, a higher fruit yield (Table 2). In all cases, yields exceed the national average of 147.35 tons per hectare [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2023]. The fruit yield of the LY and MY clusters were 30.48 and 33.47% higher than the national average, respectively, whereas the yield of the HY cluster was 95.11%. These differences may be explained by the fact that the fruit yield variable is complex (Gutiérrez et al., 2023), and influenced by the inputs used during the production process, the agronomic management of the crop and the interactions with external and internal factors of the system (Ferrández-Pastor et al., 2016).

In this context, the production system used by the farmers showed the difference in yield between the groups (Figure 4). The LY group, which plants in soil, had lower yields than the HY group, which mostly (75%) plants using hydroponics, obtaining yields ranging between 280 and 300 tons ha⁻¹, since hydroponics controls the application of water and nutrients (Andreau et al., 2015).

Another key factor in greenhouse tomato production is the use of water management technology. This study showed that producers use technologies such as fertigators or irrigation controllers, sensors, or technical advice to determine the quantity and distribution of water for irrigation. However, most producers in the LY cluster (90%) determine how much and when they irrigate based on their own experience, whereas the HY cluster uses technology or technical advice. Regarding hydroponic planting, measuring nutrient solution parameters is required to ensure the availability of macro- and micronutrients for the plant, such as pH and electrical conductivity (EC). Only a third of the producers in the LY and MY clusters measure pH and EC in the nutrient solution. However, all producers in the HY group do so, which is highly correlated with fruit yield and quality (Sánchez and Moreno, 2017).

Regarding water use efficiency (WUE), expressed as kilograms of tomato produced per cubic meter of water, the results showed that there are no significant differences between the farmer groups (Figure 4). However, several considerations should be noted: the LY cluster uses the soil production system, the MY cluster combines hydroponic and soil systems, and the HY cluster mostly uses hydroponics, making irrigation management different in each production system. For example, in hydroponics, overwatering is required to control salt concentrations, while in soil, it is generally avoided. Additionally, the information provided by farmers, mainly from the LY group, was largely based on their experience, as they lack measuring equipment. Therefore, the data should be considered only as a reference, since they were collected using the survey method as recommended by Check and Schutt (2012), and subsequently used to calculate WUE, as indicated by Feleafel and Mirdad (2014). Across all farmer groups, WUE values were low (average 17.06 kg m⁻³, Figure 4) compared to those reported by Flores et al. (2007) of 35 kg of tomato produced per m³ of water under controlled conditions. This indicates that we must work together with farmers to improve efficiency.

Once the tomato fruit is produced, in quantity and quality, producers face various challenges in placing the food on the final consumer's table. The profit the producer obtains depends on this sale. Thus, based on yield and sale price, the LY cluster has higher profits (64%) than the MY cluster because producers have lower production costs (20%). However, the cluster with the highest profits is the HY (Table 2). This is because the HY obtains the highest yields and sale prices because they produce the tomato fruit for export [Sánchez and Moreno, 2017; Sistema Nacional de Información e Integración de Mercados (SNIIM), 2022]. In addition, their investment in agricultural inputs and water management technology is greater. On the other hand, most small-scale producers (LY and MY) are not organized to make direct sales to consumers, and instead, sell the fruit to intermediaries (Table 2).

Farmers in the low and middle-income groups display the lowest performance and cost-benefit ratios, due to several factors such as the size of the production unit and limited access to investment. Therefore, from our perspective, in order to increase the productivity and profits of these two groups of producers, the solution is not to export the product, because it is essential to meet local market demand and prices are historically lower than foreign sales [Sistema Nacional de Información e Integración de Mercados (SNIIM), 2022]. Therefore, efforts should focus on training, organizing, and supporting these groups throughout their production processes. By improving the efficiency in the use of key inputs—particularly water, fertilizers, and pesticides—their productivity

can be enhanced, which in turn will lead to higher yields and profits in the near future. This is based on the results shown by Koukounaras (2021), Sánchez and Moreno (2017), and Avgoustaki and Xydis (2020).

The organization of producers to carry out each activity in the production system is essential. However, producers show little or no interest in joining organizations, mainly because they do not see the advantages of joining one, such as access to training, purchase of input, sale of products, and access to government programs [SADER (Secretaría de Agricultura y Desarrollo Rural), 2025]. In this sense, strengthening the links between government and private institutions, teaching and research institutions, and the agricultural production sector is important, as pointed out by Domínguez-Hernández et al. (2022) and Abdurrahman et al. (2023).

4.2 Critical points of the system

Based on the characterization of the greenhouse tomato production system in Texcoco, the following positive critical points were identified:

- (1) The high levels of education, with more than 50% of farmers having university degrees, favors the acquisition of knowledge and use of technology.

In this regard, Vargas-Canales et al. (2018) note that the adoption of technological innovations is related to the educational level of the farmer, since people who have participated in a process of continuous learning and development are trained to continue acquiring knowledge, skills, values, attitudes and aptitudes to improve their quality of life [UNESCO (Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura), 2020], which, in turn, can be applied to improve the agroecosystem.

- (2) The use of family labor in the LY and MY clusters, and the creation of jobs in the HY cluster, benefiting day laborers in the agricultural sector.

This aspect is particularly relevant in the Mexican context, as in 2022, 41% of the agricultural and forestry workforce was family-based. Out of this percentage, 33% did not receive a wage, while only 8% did. A similar situation was observed in the State of Mexico, where permanent family labor accounted for 75% of the workforce, consisting of 73% unpaid and 2% paid workers (INEGI, 2023b). Although family labor is unpaid, it is thanks to family employment that the small production units can be sustained and income can be generated to cover basic needs of the families. Furthermore, the United Nations consider family farming to be fundamental to the economic and social development of rural communities, potentially contributing to several Sustainable Development Goals (SDGs) (FAO and IFAD, 2019).

- (3) Productivity: in general, farmers have higher yields compared to those reported at the national level [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2023].

This productive activity is important as a complementary or main source of income for families dedicated to greenhouse cultivation.

Therefore, it is desirable to increase yield per hectare through the efficient use of natural, human, and financial resources (Zepeda-Bautista et al., 2021), as well as infrastructure. This indicates that productivity is the attribute that most strongly influences the sustainability of agroecosystems, as reported by Domínguez-Hernández et al. (2018) and Suazo-López et al. (2025) for corn and tomato.

In this context, negative critical points of the system were also observed. These aspects represent an opportunity to improve water use efficiency to achieve higher yields and better-quality fruit, contributing to the Sustainable Development Goals [UN (United Nations), 2015]. For example, the lack of support in technical advice and subsidies for expensive inputs, such as fertilizers, and limited use of technology, since the LY and MY clusters use little technology for water management. This is due the inputs and infrastructure being imported, because in Mexico, modern agriculture depends on foreign technology [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2016]. Furthermore, farmers require technical assistance for the correct application of agrochemicals, equipment, and agricultural innovations to ensure the efficient use of resources, as mentioned by Zepeda-Bautista et al. (2021).

The information provided by producers will be valuable to design and implement interventions (Domínguez-Hernández et al., 2022; Domínguez and Zepeda, 2024) that could be useful to achieve an efficient water use in greenhouse tomato production in Texcoco, with the participation of key actors in the production system for the benefit of farmers, agricultural workers, suppliers, intermediaries and consumers. In this case study, several intervention strategies were proposed. However, for the interventions to be carried out, it is necessary to plan, design, and implement (Ørngreen and Levinson, 2017) each one of them based on scientific evidence and consultation with experts (Checkland and Poulter, 2010).

4.3 Proposals for interventions to improve greenhouse tomato production systems

Based on the results obtained in this study and the analysis carried out on the greenhouse tomato production system in Texcoco, the following improvement strategies are proposed:

- (1) Strengthening the knowledge of farmers through ongoing training on the efficient use of water in tomato greenhouses toward sustainable production to take advantage of the fact that they have an average age ranging 32 and 52 years with superior and postgraduate education levels, which will help them acquire knowledge and adopt technology towards sustainable agriculture. Vargas-Canales et al. (2018) showed that the efficiency in the adoption of innovations is related to the farmer's education level, experience, and access to the extension service, and Suazo-López et al. (2025) propose training as a strategy to improve the system.
- (2) Agricultural technical assistance program. Design, establish and evaluate a technical advisor program that includes topics on the subsystems of coordination, maintenance, adaptation and production (Ferrández-Pastor et al., 2016), because the tomato yield is a complex variable due to natural, human and financial resources of the system needing to come together

simultaneously (Gutiérrez et al., 2023; Suazo-López et al., 2025). This will help producers manage their production unit as a business.

- (3) Active and continuous organization of greenhouse vegetable farmers. They have a flaw regarding the sale of tomatoes to the intermediary (73 and 94% of farmers in the LY and MY clusters), as well as the import of inputs and equipment for sustainable production, due to Mexico's dependence on modern agricultural technology. This includes machinery and software (drones, GPS systems and data analysis software), seeds and biotechnology (hybrid seeds, chemical fertilizers and pesticides) and digital technologies (mobile platforms and applications) [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2016]. Another common weak spot among horticulturists is the lack of organization to access government or private financing to acquire machinery and equipment for production, since established associations and, in some cases, financial contributions are required [SADER (Secretaría de Agricultura y Desarrollo Rural), 2025].
- (4) Financing program to acquire infrastructure, machinery, and equipment for greenhouse vegetable production. Farmers in LY and MY clusters in Texcoco earn between 31,102 and 51,012 Mexican pesos per month (Table 2), which they use to pay for their family's basic expenses. Therefore, these farmers do not have the financial resources to invest in water measurement and control equipment, nutrient solution, labor, and communications equipment. Hence, the need for financing programs.
- (5) Entailment between producers and educational, research and governmental institutions (Dominguez-Hernandez et al., 2022). Universities can have a significant impact by organizing farmers and then providing training courses and guidance, showing that technology applied to protected agriculture is neither costly nor difficult to manage. Also, government institutions can implement agricultural policies (Parra et al., 2023) so that farmers have access to training and technology to improve greenhouse tomato yield at national, regional, and local levels.
- (6) Joint efforts between researchers, companies, and producers to establish school or demonstration plots are beneficial for agricultural education and knowledge transfer. These plots offer practical learning experiences, showcase high-end technologies and practices, and facilitate farmer engagement (Kadzere et al., 2020; Mustafa et al., 2025). These plots can highlight improved tomato varieties, seedling production, sustainable production, integrated pest and disease management, marketing, and the development of new tomato products, among others, essential activities to increase tomato yield towards sustainable production.
- (7) Training workshops for vegetable farmers. In these workshops, farmers actively engage in the application of concepts and problem-solving (CAEP United States, 2025) related to the efficient use of water and nutrient resources, pest and disease control, and marketing and use of technology. To ensure their successful implementation, the integration of producers, researchers, and educational, research, and government institutions is essential. They must participate in an organized

and harmonious manner in the planning, preparing, delivering, and following up of the workshops.

Once the intervention proposals to improve the system have been defined, the next step would be to design, implement, evaluate and provide feedback on each of them, provided the producers approve them in a meeting and that the work is carried out in collaboration with the main actors of the system (Parra et al., 2023). This implementation would be in the medium term (between 2 and 3 years), considering the Mexican context described by the producers and the technological dependence on irrigation systems and infrastructure in protected agriculture [SIAP (Servicio de Información Agroalimentaria y Pesquera), 2016]. It is evident that, through the adoption of high-end water management technologies (Vargas-Canales et al., 2018) and training (CAEP United States, 2025), it is possible to improve and approach the efficiency in water use reported by Flores et al. (2007), who mention that 35 kilograms of tomato are produced per m³ of water under controlled conditions. Therefore, increasing water use efficiency and providing training will enhance the resilience of producers during critical periods of water availability, improve competitiveness and strengthen their production units and local roots.

4.3.1 Highlights and limitations

This study is a first approach to understanding the use of technology and measuring equipment for irrigation management and water supply in production units in Texcoco, and how these relate to economic and productivity parameters. The results may be useful for farmers engaged in greenhouse tomato production and serve as a basis for further studies in areas with similar weather, economic, and technological conditions. The information provided by farmers has certain limitations, as most do not keep records and manage water based on experience. Nevertheless, these studies help identify the need for interventions in these production sectors to improve input efficiency, which can lead to higher productivity and an improved standard of living for farmers. Furthermore, the number of high-income producers shows heterogeneity among groups, and producers with access to high-end technology and higher productivity represent an exceedingly small proportion of Mexican agricultural farmers.

On the other hand, this study only proposed interventions that could potentially improve the production system. Therefore, future work should focus on designing, implementing, and evaluating each intervention as described by Abdurrahman et al. (2023) and Domínguez-Hernández and Zepeda-Bautista (2025), and in the case of training workshops, evaluation was not conducted, since this type of study requires monitoring for at least two production cycles. Therefore, it is advisable to establish a continuous training program for producers, including the establishment of school plots, evaluation, and support over at least two production cycles. The report on the training workshops is in the [Supplementary material](#).

It is recommended that, in future work on characterizing the production system using the survey method, a calculated sample size be used and that the farmers who will participate in the study be selected using the probabilistic sampling method, where all farmers in the target population have equal chances of being selected in the sample.

5 Conclusion

This research makes a significant contribution to responsible production through a socioeconomic analysis of greenhouse tomato producers, with a particular focus on the use of water management technology, a limited resource. The comprehensive study offers a rigorous analysis that identifies key challenges, such as the limited use of water management technology in greenhouse production and restricted access to subsidies, technical advice and training, all of which negatively impact system productivity. In this context, interventions are proposed, and training is provided to small-scale producers using a multidimensional, systemic and transdisciplinary methodology.

Based on variables such as income, fruit yield per hectare per year, cultivation system, average irrigation, drip irrigation and use of water management technology, cluster analysis classified greenhouse tomato producers into three groups: low, medium, and high yields. The low- and medium-yield clusters showed similar tomato yields (192.27 and 196.67 tons/ha, respectively), whereas the high-yield cluster showed a higher average yield (287.50 tons/ha), with a cost–benefit ratio of 1.2, 1.5, and 3.78, respectively.

Farmers use varying degrees of water management technology, although their calculated water use efficiency (WUE) for producing 1 kg of tomatoes was similar to, but lower than, the one reported by Flores et al. (2007) (35 kg m⁻³). This is despite the fact that in hydroponics, water and nutrient application is controlled, and a greater quantity of water is required compared to soil. Therefore, the WUE value is affected by the data provided by the producers, which was not obtained through rigorous experimentation, and by the water management technology used.

Greenhouse tomato farmers use drip irrigation systems to supply water to their plants, most of which are imported. This answers the question of how to irrigate. However, when it comes to when and how much to irrigate, most farmers rely on experience, making them prone to errors and inefficient water use. Therefore, using soil moisture sensors or equipment to measure climatic parameters is necessary to more accurately determine the optimal irrigation time and the amount of water the plants require.

Each group requires improvements in its production system. The LY cluster requires greater intervention from the government and educational and research sectors to organize them, facilitate their access to technology and training that allows them not only the good use of technology and water supply, but also to record information and estimate water consumption by the crop. MY needs to consolidate itself as producers in protected agriculture. To achieve this, they should organize joint purchases of inputs to obtain better prices, improve fruit marketing, and continue training for the adoption of high-end technologies. Finally, the HY cluster, although already using technology and having established markets, still needs to increase WUE.

Based on the analysis of information provided by farmers, the hypothesis is not rejected, since farmers in the LY and MY clusters lack the technology for efficient water management, which negatively affects productivity.

Factors affecting the productivity of small-scale framers were identified, including education levels, employment, productivity, lack of technical assistance and subsidies and a limited use of technology. These findings informed the design of interventions such as ongoing

training, an extension services program, active and continuous organization, a financing program, linking producers with educational, research, and governmental institutions, and technology transfer activities. Finally, workshops were conducted to train small-scale farmers, an intervention aimed at improving their knowledge for sustainable production. Educating farmers improves their quality of life and their agroecosystem. These results are not only applicable to small-scale farmers in Mexico but can also be applied in food-producing regions worldwide with similar socioeconomic and technological characteristics.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

FS-L: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing, Investigation. JÁ-I: Investigation, Writing – review & editing, Supervision. RZ-B: Conceptualization, Supervision, Investigation, Data curation, Writing – review & editing, Writing – original draft, Methodology, Formal analysis. FD-P: Methodology, Data curation, Writing – review & editing. JR-R: Conceptualization, Writing – review & editing. LH-S: Writing – review & editing, Formal analysis, Data curation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frsus.2026.1685506/full#supplementary-material>

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