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# Sustainability analysis of the greenhouse tomato (*Solanum lycopersicum* L.) production system

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**ABSTRACT**

The sustainability of the tomato production system in greenhouses in the municipal area of Texcoco, Mexico, was evaluated using a cluster analysis for the classification of farmers and the framework for the evaluation of management systems for natural resources, incorporating sustainability indicators to evaluate sustainability. The results showed three groups of farmers considering the technology used in production: low technology level (LTL), medium technology level (MTL), and high. They differed in fruit yield (230.19 tons $ha^{-1}$ $year^{-1}$ on average), cost-benefit rate (1.31 on average), organization, water management, and greenhouse surface and equipment. Productivity was the attribute that affected sustainability the most since yield is a complex variable due to the conjunction of natural, human, and financial resources that affect the environmental, social, and technological dimensions. Fruit yield was slightly higher than the reference value (180.32 tons $ha^{-1}$ $year^{-1}$) at 53.53%, 18.44% and 1.8% in the high, medium, and low technological level clusters, respectively, whereas net income and the cost-benefit rate had lower values than the reference (1034326 MEX$ and 1.62, respectively) for the LTL and MTL clusters. The information obtained helps generate a baseline and strategies to improve the sustainability of the system.

## 1. INTRODUCTION

Agriculture plays an important part in the 17 sustainable development goals [1]. This encompasses all activities through which human beings manage and transform resources to produce food [2]. Water is the main input to produce them; out of the total water on our planet, only 0.003% is fresh water [3], of which 70% is used for food production [4,5]. In Mexico, the situation is even more difficult since up to 76% of the water consumed is used in agriculture, which has caused overexploitation of underground water [6] in the central, north, and northeastern areas of Mexico [7]. The high rate of water consumption in agriculture makes it necessary to improve the efficiency of application through different irrigation techniques such as drip and sprinkler irrigation [8–10], and innovative systems [11]. In this sense, protected agriculture is an agricultural system in which edaphoclimatic conditions can be controlled to a certain extent that helps increase yield, improve quality, alter conventional crop cycles, and use products when production in the open faces limitations, using protection techniques such as greenhouses, hydroponics, irrigation systems, and others [12–14].

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Studies have shown that the change in the production system from the open air to a protected one can increase water use efficiency (WUE). Combining closed hydroponic recirculation systems with semi-closed greenhouses would reduce plant transpiration by half or more [15], application of 120% of medium irrigation quota in drip irrigation in three physiological stages of tomato [13] and use of peat moss-perlite mixture and nutrient film technique can save irrigated water from 94% to 123% [14]. This is because the integration of different areas of knowledge allows us to offer comprehensive solutions [10,13,15]. In addition, these systems have been complemented with fertigation equipment that injects nutrients into the crops, along with the water [13], for example, in the case of tomato crops, the availability of estimators allows for the design of automatic fertigation schemes in greenhouses, minimizing the water supplied while meeting the crop's needs [16]. However, this equipment comes mainly from Europe and Asia, therefore, their average cost is 258,000 Mexican pesos [17], making them scarcely accessible for small-scale farmers. This is an area of opportunity for the generation of Mexican technology, thus avoiding the costs of maintenance and importing of foreign equipment [18].

To carry out the comprehensive maintenance of a system, it is crucial to know it. Therefore, some authors have characterized agricultural productive processes considering water use in agriculture [19], years of experience and education level of farmers [20–22], land and nutrient use, orchard design, economic efficiency, labor [23], crop type, investment options [24], plot size, use of improved seeds, and crop yield [22]. Additionally, farmers in the maize agroecosystem [25] and those in greenhouse tomato production [24,26] have been classified and characterized. These sustainability analyses are useful for defining the system's baseline and, in this way, proposing improvement interventions [2,27]. For example, in India, the analysis of 31 sustainability indicators showed that the production of fruits, vegetables, legumes, and oilseeds must increase by 50%–100%, while cereal production should be reduced by 50%, which would lower the environmental footprint by 10% [28]. In Spain, measuring the environmental and climate impact of the organic olive sector would enable policymakers to design better policies to increase production [29]. In coffee production in Colombia, agroecology education, marketing strategies, and the loss of natural resources were evaluated to design effective strategies that promote sustainability [30].

Based on the above, it can be summarized that research related to the characterization of agroecosystems focused on WUE includes protected agriculture as a technique that increases WUE [12,14] and fertigation [13] to find a balance between productivity and sustainability [28], which leads to technological dependence on equipment and inputs in some countries like Mexico [17]. Regarding the characterization of farmers and the evaluation of the sustainability of agroecosystems, farmers express concern about water availability and its management through irrigation [19], as well as their experience and characteristics in food production, age [20–23], and their classification based on the socioeconomic and environmental characteristics of their production [24–26]. These are useful for proposing interventions, for example, in the production systems of fruits, vegetables, legumes, cereals, olives, and coffee [28–30]. However, according to the results obtained from the literature on this topic, only a few authors have studied the analysis of sustainability focused on WUE in protected agriculture. This analysis is fundamental for designing interventions with a systemic, multidisciplinary, and transdisciplinary approach [2,27,28] for comprehensive improvement. Due to this, farmers were classified, and the sustainability of the greenhouse tomato production system was evaluated, with emphasis on the use of technologies for water management in the municipal area of Texcoco, State of Mexico, Mexico. This is under the assumption that greenhouse producers do not have the technology required for efficient water management, which affects the sustainability of the system.

## 2. MATERIALS AND METHODS

### *2.1.* Geographic and Socioeconomic Context

The study was carried out in the municipal area of Texcoco, located on the geographic coordinates between 98º 39' 28" and 99º 01' 45" West and between 19º 23' 40" and 19º 33' 41" North [31] at an altitude of 2246 masl [32], in the eastern portion of the State of Mexico, Mexico (Fig. 1). According to the Köppen classification, the climate is warm with rainfalls in the summer, an annual average temperature of 16.4°C, and an average annual rainfall of 618.5 mm [33].

According to the 2020 census, the municipal area of Texcoco has a population of 277,562 inhabitants, out of which 51.4% are females, and the rest are males; its population density is 648.3 inhabitants km$^{-2}$ and 60.8% of its population is economically active. Regarding education levels, 44.8 and 24.4% have basic and higher education levels, respectively, and 66% of the population is affiliated with healthcare services [34].

Out of all the water used in the region of Texcoco, 95% is taken from the underground [35]. However, according to the CONAGUA [7], there is a deficit in the availability of water in the aquifer of Texcoco of over 111 million m$^3$, causing a reduction in the water table of the aquifer, along with the absence of any campaigns for the care of water, and so they relate with the care of the environment [35]. The problem of water availability may worsen in the near future while the population grows continuously [36], as well as the production of food [37], and both of these cases require water. In the year 2021, 11,879.7 and 530 hectares of fruits and vegetables were planted in Mexico and the State of Mexico, respectively, whereas in the municipal area of Texcoco, 84.5 were planted in greenhouses of both ornamental plants and produce [38].

### 2.2. Target Population

The study focused on the 143 greenhouses for the production of produce and ornamental plants in the municipal area of Texcoco, State of Mexico, Mexico [39]. The size of the sample was calculated using the equation proposed by Malhotra [40]: $n = \frac{Z^2 pqN}{NE^2 + Z^2 pq}$, where n is the size of the sample to be calculated, N is the population studied, Z is normal scoring, E = is the estimation of the error, p is the probability of finding the desired characteristic in the population studied, and q is the population of not finding the desired characteristic, that is, 1-p. Therefore, considering N = 143, Z = 1.64, E = 10%, and *p* and q = 0.5, the sample calculated was 45 farmers with greenhouses, 31.46% of the total.

### 2.3. Classification of Farmers

In order to classify the farmers, a structured survey was designed with six sections: General information about the farmer, greenhouse type and equipment, irrigation systems used in the greenhouse, production, planter trays, crop management, harvest and marketing, amount and source of water used to produce weather conditions that affect the production of ornamental plants and produce. The farmers were chosen with a non-probability sampling for convenience due to accessibility and the proximity to the researcher [41]; the fact that farmers plant in greenhouses was taken as an inclusion criterion. Forty seven surveys were conducted on the farmers between May and September of 2021 using Microsoft forms® and in person in the production units. A database was created using Excel® (Microsoft Corp, Redmond, WA, USA) to capture the variables obtained with the survey and close revision of the data; this simplified the information management.

The variables of greenhouse surface, tomato fruit yield in the 2021 production cycle, price for sale in the period between 8 and 30 MEX$ kg$^{-1}$, greenhouse cost, cost of the plastic, cost of infrequent activities (purchase of substrate, padding and plastic bag), labor, total incomes and expenses in the greenhouse tomato production system, and the profit obtained in the production were evaluated with a principal components analysis (PCA) to determine which variables of the survey contribute the most towards the variability of the data. This selection was made to reduce the dimensionality of the system and to facilitate the interpretation, visualization, and comprehension of the interactions between the observations [42]. Principal components 1 and 2 were used in the cluster analysis [43].

The cluster analysis was used to determine the groups of farmers, considering the level of technology used by greenhouse tomato farmers to use human, natural, technological, and economic resources efficiently in the municipal area of Texcoco, State of Mexico, Mexico [42]. The hierarchical cluster models were created using the Euclidean distance method to find the distance between the observations and Ward's criterion to optimize the minimum variance within the clusters

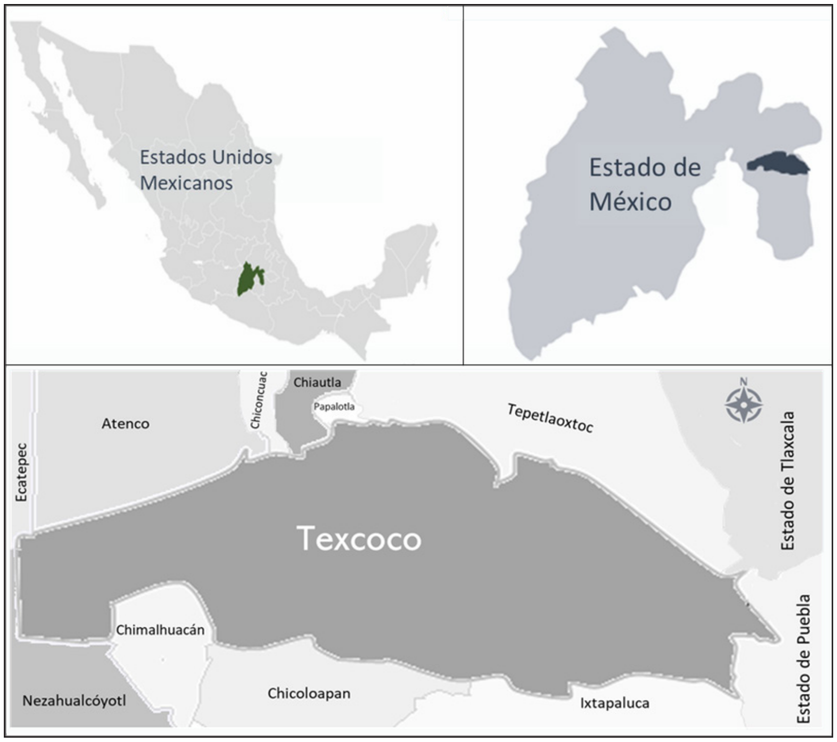


**Figure 1.** Geographic localization of the municipal area of Texcoco, Mexico State, Mexico.

[43]. This analysis helps add and characterize the observations in each cluster and then obtains the means and percentages of the variables studied [44]. The farmer classification process and the statistical analyses were carried out using the Statistical Analysis Software [45].

## 2.4. Sustainability Indicators and Analysis

To evaluate the sustainability of each one of the clusters obtained, the MESMIS (Marco para la Evaluación de Sistemas de Manejo Incorporando Indicadores de Sustentabilidad) methodology was used [46,47]. This study measured 14 indicators (Table 1), and four dimensions of sustainability were represented: economic, environmental, and social via six attributes, defined by López-Ridaura *et al.* [47] and Dominguez-Hernandez *et al.* [24], followed by the technological dimension, with the attribute of use of technology in agricultural production [48] for the comprehensive improvement of the greenhouse tomato production system. Indicators were calculated, and the units of reference were defined based on reports found in the literature and on indicators obtained in the surveys (Table 1). Productivity was chosen as the main economic attribute to provide information on the possible effect the fruit yield has on the decision to plant tomatoes, other produce, or flowers in a greenhouse and on the efficiency in the use of human, natural, financial, and technological resources.

The attributes of stability, resilience, and reliability were evaluated for the availability and conservation of productive resources to ensure economic activity in time. These attributes are also related to the adequate integration of economic activities with the environment, as well as to the vulnerability of the system to external hazards [24]. The attributes of adaptability and self-sufficiency are part of the social dimension. The former refers to the ability of the system to evolve and learn to adapt to the new conditions imposed by new physical and socioeconomic surroundings; the attribute of self-sufficiency helped evaluate the ability of control and ability of respond of the actors that manage the system. Finally, the technological dimension refers to the selection of technological tools to be used in the production system to efficiently use the resources [49].

To calculate the sustainability indicators used in both the clusters and the reference values (Table 1), the following considerations were used: 1) Net income: Calculated using the average net income of each farmer in Texcoco, México; 2) Cost-benefit rate: Carried out using the average net income divided by the average production cost (2736970 MEX$/1702644 MEX$ $ha^{-1}$ $year^{-1}$); 3) Incidence of pests and diseases, weeds and organization of farmers: The relative frequency of the farmers that reported the presence of these in the greenhouse tomato crops and that actively belong to an organization, was calculated; 4) Unpaid family workforce: The number of farmers that use unpaid family workforce and which actively participate in the production unit was recorded; 5) Level of self-funding: estimated using the government subsidy divided by the total production cost (1702644 MEX$ $ha^{-1}$ $year^{-1}$); 6) Tomato self-sufficiency: estimated based on the number of farmers who produce ≥72.64 kg $year^{-1}$, which is the annual consumption for a 4-people family [34,38]; 7) The level of technology: Estimated based on the number of farmers who have equipment for irrigation management (drip irrigation system, fertigator, and irrigation programmer), greenhouse equipment (heaters, nebulizers, automatic curtains, and thermal screens), and measurement equipment (pH, conductivity, temperature, and relative humidity meters).

The reference values in Table 1 were established or calculated using the following considerations: 1) The national average yield for greenhouse tomatoes in 2021 was used [38]; 2) Water use efficiency: calculated with the tomato fruit yield and the water used to produce it [50]; 3) Literacy: the literacy reference was of 98.03%, the average value in the municipal area of Texcoco [34], which is the percentage of the population aged ≥15 with some level of education; and 4) For the rest of the indicators, the mean value resulting from the survey was placed as the reference value.

**Table 1.** Social, economic and environmental indicators, reference values used in sustainability analysis of the production of tomato in greenhouses in the municipal area of Texcoco, State of Mexico, Mexico.

| Attribute | Indicator | Measurement | Reference unit |
|---|---|---|---|
| Productivity | Fruit yield | t $ha^{-1}$ $year^{-1}$ | 180.32 [34] |
| | Net income | Estimation: Total income–Total Costs (MEX$) | 1034326 [Survey, 2021] |
| | Benefit-to-cost ratio | Estimation: total benefit/total costs | 1.61 [Survey, 2021] |
| Stability, resilience and reliability | Water use efficiency | Fruit yield/used water | 0.04 kg $l^{-1}$ [46] |
| | Pests and diseases incidence | Survey: (producers that report pest incidence/total producers)*100 | 100% with pest incidence [Survey, 2021] |
| | Weed incidence | Survey: (producers that report weed incidence/total producers)*100 | 100% with weed incidence [Survey, 2021] |
| | Biological or organic control of pests and diseases | Survey: (producers who carry out biological or organic control/total producers)*100 | 12% with biological or organic control [Survey, 2021] |
| | Manual weed control | Survey: (producers who carry out manual weed control)*100 | 66% with manual weed control [Survey, 2021] |
| Adaptability | Literacy | Literacy Survey: literate producers | 98.03% value average in the municipality of Texcoco [30] |
| | Unpaid family labor | Survey: number of producers using family labor and participating in production | 22% Unpaid family labor [Survey, 2021] |
| | External input dependency (IED) | Estimation: EID=(external input cost/total input cost)*100 | 100% EID with the mean fruit yield [Survey, 2021] |
| Self-reliance | Self-financing level (SF) | Estimation: SF=(governmental subsidy/total production costs)*100 | 100% of the producers are self-financed [Survey, 2021] |
| | Tomato self-sufficiency | Estimation: producers that obtain fruit yield ≥ 72.64 kg (annual consumption for a family of 4 members) (SIAP, 2021, INEGI 2021) | 100% of producers satisfy their tomato needs [Survey, 2021] |
| | Producer organization. | Estimation: (producers that are associated/total producers)*100 | 12% producers are part of a farm organization [Survey, 2021] |
| Technological Level | Technology for irrigation management | Estimation: (number of producers with technology for irrigation management/ total producers)*100 | 65% producers with technology for irrigation management [Survey, 2021] |
| | Greenhouse equipment | Estimation: (number of producers with greenhouse equipment/total producers)*100 | 50% producers with greenhouse equipment [Survey, 2021] |
| | Measurement equipment | Estimation: (number of producers with measurement equipment /total producers)*100 | 80% producers with measurement equipment [Survey, 2021] |

After measuring every indicator, the value obtained was compared with the reference value, thus assigning a score (pondered value) from 0 (worst) to 10 (best) to the indicators of each cluster in order to represent them in the AMOEBA diagram. A score of 5 (intermediate) was assigned to the reference values to create a basis for comparison.

## 3. RESULTS

### 3.1. Classification of Greenhouse Tomato Farmers

The variables for the cluster analysis were selected using the first two principal components resulting from the PCA that explained 62% of the total variability: 41% and 21%, respectively. Principal component 1, named the subsystem of the production economy, is formed by the variables of income, profit, price of the tomato, and greenhouse surface with values of 0.47, 0.46, 0.43, and 0.40, respectively. Meanwhile, Principal component 2, named subsystem of maintenance, is formed by expenses and labor with weights of 0.61 and 0.60. These variables are important in the sustainability of the production unit because, if expenses are reduced, more profit could be made, and therefore, higher cost/benefit rates [48,51,21].

The cluster analysis classified greenhouse tomato farmers in Texcoco into three groups (Fig. 2), the characteristics of whom were taken from the database resulting from the survey. Based on the amount of technology used in the production system proposed by Mundo-Coxca *et al.* [48], the groups were named low technology level (LTL), medium technology level (MTL), and high technology level (HTL), and they are described in the following sections.

#### *3.1.1. Low technology level*

The majority of farmers (61%) are grouped in this conglomerate. Their average age is 49, with an elementary school education (15% of the farmers surveyed), high school (30%) and postgraduate degrees (10%). Likewise, this group showed the incorporation of women (30%) into greenhouse tomato farming.

The average surface of the greenhouses to produce tomatoes is 720 $m^2$, out of which 65% have basic equipment (they only have drip irrigation systems) and only 10% have more equipment (along with the drip irrigation systems, they have two or more machines, such as nebulization, shade mesh, automatic vents, humid walls, or heating). On the other hand, 40% of farmers have no measuring equipment (pH, conductivity, temperature, relative humidity, or radiation meters), and 10% of them have four or more measurement apparatuses.

Regarding crop management, most farmers (75%) have a soil crop system, and the rest are in hydroponics. To program their irrigation, 30%, 65%, and 5% of farmers rely on a programmer, do it manually,

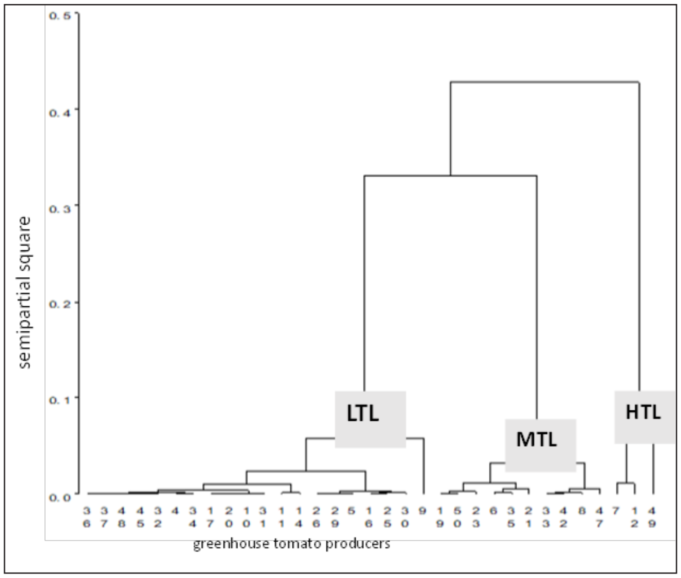


**Figure 2.** Dendrogram of the generated clusters grouping greenhouse tomato farmers in the municipal area of Texcoco, State of Mexico, Mexico. The clusters are denoted by their acronym: LTL, MTL, and HTL.

and use a fertigator, respectively. The water used for tomato production is taken from a well (70% of farmers), and 10% uses water from irrigation channels.

Finally, all the farmers from this group sell their tomato fruits fresh; most (80%) sell their products to an intermediary and the rest sell them to the end consumer. The farmers have an average yield of 188.3 ton $ha^{-1}$, and to sell this, they invest an average of 1,864,533 Mexican pesos per hectare (MEX\$ $ha^{-1}$), out of which 854,000 MEX\$ $ha^{-1}$ are allotted to labor and 380,529 MEX\$ $ha^{-1}$, to the cost of the nutrient solution, keeping an average of 2,188,250 MEX\$ $ha^{-1}$ in income.

### *3.1.2. Medium technology level*

This group is composed of 30% of the surveyed farmers with an average age of 47 with a university (40%) and High School education (20%) and without the participation of a woman. The production of tomato in greenhouses is the main source of income for 40% of farmers, and it is a complementary source of income for 50% of them, whereas the remaining 10% plant in the winter for other purposes, such as research. The average greenhouse surface is 6,180 $m^2$. Regarding the resources, they were built with, 40% of them did so with governmental support, and the other 40%, with a combination of their own resources and governmental support.

In this group, 50% of the greenhouses have basic equipment (only drip irrigation), 30% a medium level (three machines) and the rest have more equipment (four or more machines). Regarding measurement equipment, 20%, 20%, 20%, and 40% of greenhouses have no measurement equipment. They have one or two or three and four or more measurement devices, respectively.

The most widely used planting system is in the soil (60%), and the rest uses hydroponics. To program the irrigation, 20% of farmers use a programmer, 40% do it manually, and the remaining 40% use a fertigator. For the production of tomatoes 60%, 20%, and 20% of farmers take water from wells, use rainwater and well water, and have a spring as their source, respectively.

The majority of farmers (90%) sell the fresh tomato fruits to an intermediary, and the rest sell to both an intermediary and to the end consumer. The average tomato yield is 219 tons $ha^{-1}$ for a production of 2,105,500 MEX\$ $ha^{-1}$. Regarding expenses, the average was 1,266,970 MEX\$ $ha^{-1}$, out of which 345,497 MEX\$ $ha^{-1}$ went to the nutrient solution and 786,000 MEX\$ $ha^{-1}$ to the cost of labor.

### *3.1.3. High technology level*

The third group is formed by 9% of the greenhouse tomato farmers in Texcoco. Their average age is 27, with a university education and a higher participation of women (67%). This group is composed of the youngest farmers and those with the highest education levels.

The production of greenhouse tomatoes, for most of the survey respondents (67%), is their main source of income, and for the rest, it is a complementary source. They have greenhouses with an average size of 22,500 $m^2$ and to build them, they invested their own resources (33%), and the rest pays rent. Greenhouses have basic, medium, and high equipment levels, 33% each, and all have full measurement equipment.

The most widely used irrigation system by farmers is hydroponics (67%), and the rest is in the soil. They all program their irrigation with fertigation, take water from wells, and export their production with an average yield of 283 t $ha^{-1}$ and an average income of 8,500,000 MEX\$ $ha^{-1}$. Farmers spend 2,075,625 MEX\$ $ha^{-1}$ to produce, out of which 658,517 MEX\$ $ha^{-1}$ is to cover the cost of the nutrient solution and 1,120,000 MEX\$ $ha^{-1}$ to the cost of labor.

## 3.2. Sustainability Indicators

This is the first sustainability analysis of the production of tomato in greenhouses in the municipal area of Texcoco, State of Mexico, Mexico; therefore, reference values are used to generate a baseline. In addition, by including the farmer typology, the existing subsystems are compared within the tomato production systems in the municipal area. To facilitate the analysis of the indicators measured in the different clusters, they were grouped in their respective dimensions: economic, environmental, social, and technological, and they are described in the following sections.

### *3.2.1. Economic dimension*

For the three clusters, the values obtained in the indicator of fruit yield per hectare values higher than the reference were found (Table 2). However, the values of the clusters LTL and MTL were slightly higher than the reference value at 1.8% and 18.44%, respectively, whereas the HTL had a value 53.53% higher than the reference. This was reflected in the net income and cost-benefit rate with values above the reference in 295.08% and 136%, respectively. The opposite was found in the LTL and MTL groups, which had values below the reference (Table 2) in 80.09% and 48.43% for net income and 87.02% and 49.62% for the cost-benefit rate.

### *3.2.2. Social dimension*

The majority of the values of social indicators are greater than the reference values, except for the indicator of family labor, which had a lower value (Table 2). In the LTL cluster, the unpaid family workforce is used to perform activities in the greenhouse tomato production system by 195.45% more than the reference value (Table 2), whereas MTL and HTL do not use unpaid family labor.

Regarding the literacy factor, in all clusters, the greenhouse tomato farmers in Texcoco, State of Mexico are literate and have education

**Table 2.** Clustered values for the economic and social indicators used in the MESMIS sustainability analysis of the production of tomato in greenhouses in the municipal area of Texcoco, State of Mexico, Mexico.

| Indicator | Technology level | | | Reference |
|---|---|---|---|---|
| | Low | Medium | High | |
| Fruit yield (t ha$^{-1}$) | 188.25 | 219.00 | 283.33 | 180.32[1] |
| Net income (MEX$) | 323,717.30 | 838,529.20 | 6424,374.67 | 1034,326[2] |
| Benefit-to-cost ratio | 0.17 | 0.66 | 3.10 | 1.61[2] |
| Unpaid family labor (%) | 65 | 0 | 0 | 22.00[2] |
| Literacy (%) | 100 | 100 | 100 | 98.03[3] |
| External Input Dependency (EID, %) | 100 | 100 | 100 | 100.00[2] |
| Self-financing level (SF, %) | 100 | 100 | 100 | 100.00[2] |
| Tomato self-sufficiency (%) | 100 | 100 | 100 | 100.00[2] |
| Producer organization (%) | 5 | 30 | 0 | 12.00[2] |

[1][34], [2][Survey, 2021], [3][30], MEX$ ha$^{-1}$=Mexican pesos per hectare.

**Table 3.** Clustered values for environmental and technological indicators used in the MESMIS sustainability analysis of the production of tomato in greenhouses in the municipal area of Texcoco, State of Mexico, Mexico.

| Indicator | Technological level | | | References |
|---|---|---|---|---|
| | Low | Medium | High | |
| Water use efficiency (kg l$^{-1}$) | 0.01 | 0.01 | 0.01 | 0.04[1] |
| Pests and diseases incidence (%) | 100 | 100 | 100 | 100[2] |
| Weed Incidence (%) | 100 | 100 | 100 | 100[2] |
| Biological or organic control of pests and diseases (%) | 15 | 0 | 0 | 5[2] |
| Manual weed control (%) | 95 | 70 | 33 | 66[2] |
| Technology for irrigation management (%) | 35 | 60 | 100 | 65[2] |
| Greenhouse equipment (%) | 35 | 50 | 66 | 50[2] |
| Measurement equipment (%) | 60 | 80 | 100 | 80[2] |

[1][46], [2][Survey, 2021].

levels between elementary school and postgraduate studies. Values are 4.93% higher than reports by INEGI [34]. A similar situation was observed in the indicator of dependence on external inputs, where the farmers of the three clusters depend on imported inputs to carry out management activities to produce tomato in greenhouses (Table 2).

### *3.2.3. Environmental dimension*

The values of WUE and biological or organic pest and disease control were lower in comparison with the reference values. The clusters LTL, MTL, and HTL had similar values for WUE (Table 3) and resulted in lower values than the reference by 75%. On the other hand, the biological or organic control of pests and diseases was only carried out by a small portion of the group of LTL farmers (15%), which is higher than the reference value by 200%, since the tomato farmers in the MTL and HTL groups have production surfaces of 6,180 $m^2$ and 22,500 $m^2$, respectively, and higher investments in the process of planting in comparison with the LTL group.

On the other hand, for the three clusters, the values for the incidence of pests, diseases, and weeds are equal to each other and to the reference value (Table 3). This is due to all farmers having reported the presence of insects, mites, nematodes, fungi, and weeds. The values of the indicator manual weed control for clusters LTL and MTL are higher than the reference value by 43.94% and 6.06%, respectively, whereas for the cluster HTL, the value was 50% lower in comparison with the reference value.

### *3.2.4. Technological dimension*

In the clusters of low and medium technology levels (MTLs), the values of the indicator technology for irrigation management are lower (46.15% and 7.69%, respectively) than the reference value. However, in the group HTL, a higher value (53.85%) than the reference value was observed (Table 3).

The values of the indicators greenhouse equipment and measurement equipment in the HTL cluster were higher (32% and 25%, respectively) in comparison to the reference values, whereas in the MTL cluster, the values were equal to the reference value (Table 3). The opposite was observed in the LTL cluster, where the values were lower (30% and 25%, respectively) than the reference values.

## 3.3. Sustainability Analysis

The results obtained helped ponder the indicators of sustainability to generate an AMOEBA diagram, which constitutes the graphic representation of the sustainability of the production system. The radial series or AMOEBA (Fig. 3) corresponds to the clusters evaluated and shows, in correspondence with the results mentioned in the previous sections, whether the indicators of each cluster have reached the best value possible (in this study, 10) or even reached the baseline level (reference system with a value of 5) [24].

In the greenhouse tomato production system, productivity was the attribute that affected the sustainability of the three groups of farmers.

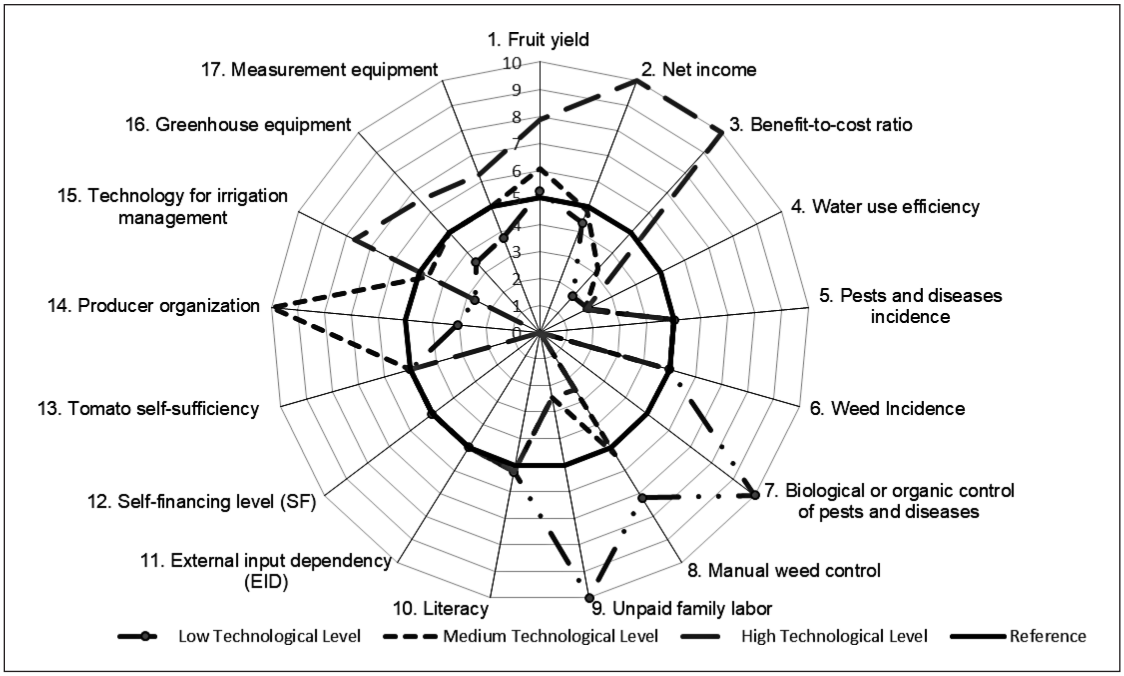


**Figure 3.** AMOEBA diagram for the measured sustainability indicators of the three clusters of tomato producers in Texcoco, Mexico State, Mexico. The sustainability attributes group the indicators as follows: Productivity (1–3), Stability, resilience, and reliability (4–8), Adaptability (9–11), Self-reliance (12–14) and technological level (16–17). The variables were standardized on a scale from 0 (worst) to 10 (best), where the reference system has an overall score of 5.

Fruit yield was the most important indicator, in consequence, fruit yield is correlated with the total income ($r$ = 0.60), as well as with efficient water use, nutrient solution, and labor [23]. Fruit yield was slightly higher than the reference value in the High, Medium, and LTL groups, respectively, whereas net income and the cost-benefit rate have lower values than the reference value for the LTL and MTL groups (Fig. 3, Table 3).

The fruit yield in LTL was slightly higher than the reference value (180.32 t $ha^{-1}$) [38] and lower than the yield obtained by farmers in clusters MTL and HTL. The highest yield was obtained in the HTL cluster, 53.22% higher than the reference value (180.32 t $ha^{-1}$) [38]. A similar situation was observed in the variables of net income and cost-benefit rate.

Unpaid family labor was observed to be mostly used by farmers with LTLs since they plant on small surfaces. Therefore, all agricultural activities are performed directly by the farmer with the help of a family member. The opposite is true in the MTL and HTL groups, which plant larger production surfaces (6,180 $m^2$ and 22,500 $m^2$, respectively) in comparison with LTL and with an entrepreneurial vision in which the family workforce is not convenient because it is insufficient to perform all activities inside and outside the greenhouse.

The farmers of the LTL, MTL, and HTL clusters had similar values in the WUE (0.01 kg $l^{-1}$) and they were lower than the reference values (0.04 kg $l^{-1}$) [50]. Regarding biotic factors such as weeds, pests, and diseases, all greenhouse tomato farmers report an incidence of weeds, pests, and diseases because many of these find favorable conditions inside the greenhouse [52], such as temperature and relative humidity. However, only a small part of LTL farmers carries out biological or organic control of pests and diseases due to the small size of their production units, and it is easy for them to prepare or purchase organic pesticides. Meanwhile, in the MTL and HTL groups with higher production surfaces in comparison with the LTL group, the use of biological or organic pesticides is not practical or attractive for them.

## 4. DISCUSSION

Based on the technology used to produce greenhouse tomato in the municipal area of Texcoco, Mexico, the farmers were grouped into Low, Medium, and HTLs [48], who share characteristics and production subsystem activities related to crop management. In general, the farmers are adults (average age between 27 and 49) with an intermediate-higher, superior, and postgraduate education level, which will help them adopt innovations in protected agriculture. Meanwhile, Vargas-Canales *et al.* [53] showed that the efficiency in the adoption of innovations is related to the farmer's education level, experience, and access to the extension service. Likewise, it was shown the incorporation of women (average 48.5%) into greenhouse tomato farming because the agricultural activity is carried out on small surfaces.

The difference in all three groups was fruit yield because it is a complex variable due to natural resources (soil, sunlight, air, water, weeds, pests, and diseases), human resources (labor, organized farmers, agrochemical companies, irrigation systems, and greenhouses) and financial resources of the system needing to come together simultaneously [12]. There are specific characteristics between LTL, MTL, and HTL groups.

In general, LTL farmers in the municipality of Texcoco, Mexico, face a lack of empirical-technical knowledge in greenhouse tomato production because this activity is relatively new in Mexico, having started in 1999 with a small production area between 721 ha and 25,000 ha in 2016, and they do not have training. In addition to this, these farmers do not have the financial resources to invest in water measurement and control equipment, nutrient solutions, and labor. Managing these factors is essential to move towards sustainable production development [23]. Addressing this issue, an integrated effort is required between producers and educational, research, and governmental institutions [2,27]. Universities can have a significant impact by organizing farmers and then providing training courses and guidance, demonstrating that technology applied to protected agriculture is neither costly nor difficult to manage. Additionally, it is essential to implement agricultural policies [29] that enable small farmers to access training and technology to improve productivity in their production units.

According to the experience of MTL farmers, they have a weakness with the sale of tomatoes to the intermediary because if they sold the tomato at the Central de Abastos (CA) in Mexico City, the price per kilogram could be 58% lower than if they sold it to the end consumer. For example, 1 kg of tomato sold at the CA for $12.00 MXN, costs $20.00 MXN in local stores for the end consumer. This indicates that the profitability of the production unit can increase by more than 50% if the production is sold directly to the final consumer. One strategy to avoid intermediaries in selling fresh tomatoes is to use communication technologies. According to INEGI [54], in 2023, 95% of households in Mexico had cell phones; therefore, this technology and available applications should be used to promote the product and sell it directly to consumers. This can be done with the support of an educational institution to train farmers in the use of these technologies and help them benefit from them.

On the other hand, in the group of HTL farmers, the size of the production unit, fruit yield, and the educational level of the production team enabled them to acquire and use measurement equipment, as well as to adopt greenhouse hydroponics for tomato production. At that time, they achieved higher yields and profits through the use of hydroponics [12,14]. Another favorable factor was that the farmers held university and postgraduate degrees, giving them a competitive advantage in better analyzing the benefits of technologies [53] that can improve the efficiency of inputs like water, chemical fertilizers, and pesticides to increase productivity with minimal environmental impact [10,28], thus contribute to responsible production and consumption [1].

The three groups of greenhouse tomato farmers do not have the same economic, environmental, social, and technological sustainability rates, the latter being the dimension with the greatest difference between them. Water management technology, greenhouse equipment, and apparatuses to measure environmental and management variables that influence the tomato crop are decisive for the sustainability of the system; however, there is a technological dependence on other countries. This variable is complex [15], hence the need to control it.

For the three clusters, fruit yield was slightly higher than the reference value for the Low, Medium, and HTLs, respectively, whereas net income and the cost-benefit rate have lower values than the reference for groups LTL and MTL. On the contrary, the values of WUE, and biological or organic pest and disease control were lower in comparison with the reference values because this activity is not practical or attractive for farmers because the use of biological or organic pesticides is more preventive than curative in the short term, since farmers ensure the use of agrochemicals more, without planning for the control of pests and diseases [55].

Farmers in the MTL and HTL groups, with larger production areas and higher profits, prefer using agrochemicals for pest and disease control because these products act more quickly and effectively and are more widely available on the market compared to organic products. These farmers are not willing to try products they do not know, primarily because they are not aware of the benefits of using organic products for the health of the farmers, the final consumer, and the environment [56,57]. Therefore, a key element for the comprehensive improvement of the system is training in environmental education with an emphasis on the efficient use of organic products to prevent and control pests and diseases affecting tomato crops in hydroponics and greenhouses. On the other hand, farmers in the LTL group indicated that their main reason for using organic products is their lower cost compared to agrochemicals, and in some cases, they can prepare these products themselves.

The increase in productivity may represent the means to ensure the sustainability of the tomato production system in greenhouses in the municipal area of Texcoco via the use of technology to increase WUE, the application of biological, organic, and physical methods to control pests, diseases, and weeds, the organization of farmers and access to funds.

In the greenhouse tomato production system, productivity was the attribute that affected the sustainability of the three groups of farmers, and fruit yield was the most important indicator since it is a complex variable resulting from natural resources such as soil, sunlight, air, water, weeds, pests, and diseases coming together simultaneously [12], along with human resources, such as labor, organized farmers, agrochemical companies, irrigation and greenhouse systems, and financial resources for the purchase of inputs and system transformation activities [58]. Similar results were reported by Dominguez-Hernandez *et al.* [24] when they evaluated the sustainability of the maize agroecosystem in Ahuazotepec, Puebla, and Suazo-López *et al.* [59] when planting tomato in hydroponics and in a greenhouse.

The greenhouse tomato yields obtained by farmers in Texcoco are higher than the national average reported by the SIAP [38] (180.32 t $ha^{-1}$), unlike the net income and cost-benefit rate, due to the lower price of tomato reported by farmers and the cost of production inputs [48]. As a reference, the lowest and highest price for tomatoes in Mexico City, Mexico's Central de Abasto (wholesale market), was 5.5 and 21 MEX$ $kg^{-1}$, respectively, for 2021 [60], and the cost of inputs such as fertilizers, which most farmers purchase in the local municipal market of Texcoco were 10% higher than the average for the markets in the whole country [60].

The lowest yield was obtained in the HTL cluster because most production units are small (720 $m^2$). These greenhouses have basic equipment and 40% of farmers have no measurement equipment such as thermometers, conductivity meters, potentiometers, or hygrometers to measure air temperature and humidity, water conductivity, and pH in order to make decisions and control the environment of the greenhouse and the nutrient solution [12,52]. In addition, most of them use the soil as a planting system, possibly due to the need for a greater investment in hydroponics, as well as a greater use of inputs such as fertilizers. However, hydroponics allows for greater control over the nutrition of the plant [61].

The highest yield was obtained in the HTL cluster because this group of farmers has the highest production surface (22,500 $m^2$ on average), and their greenhouses are better equipped (33% have high-standard equipment) and measuring equipment. In addition, all farmers plant in hydroponics, and they use technology for the management of water and nutrition such as fertigators and irrigation programs. This indicates that this group has a higher efficiency in the use of resources in comparison with conglomerates LTL and MTL due to the use of technology [49]. A similar situation was observed in the variables of net income and cost-benefit rate. These results are consistent with reports by Rezvani *et al.* [62], who obtained a cost-benefit rate of 2.33 and 3.06 in the open-air and greenhouse tomato planting systems, respectively.

The advanced technology and hydroponics used by farmers in the HTL group allow them to control the supply of water, nutrients, and irrigation frequency with greater precision [12,52,61]. For instance, an irrigation programmer controls the volume and frequency of irrigation (more than 15 irrigations per day) [59]. This enables better adjustment of water and nutrient supply in a hydroponic cultivation system according to plant requirements, resulting in higher yields and greater fertilizer efficiency [10]. On the other hand, for farmers in the LTL and MTL groups to access this technology, it is necessary to design and implement interventions based on system characterization, involving farmers, research institutions, government entities, and the end consumer [2,27] to acquire measurement equipment, greenhouses, and infrastructure; as well as to provide training in responsible production [1], environmental education, and other areas according to each farmer's needs.

The education level of the farmers is an important indicator for sustainability [22], should they acquire the knowledge to satisfy current needs without jeopardizing the ability of future generations to satisfy their own needs [1]. Greenhouse vegetable farmers in Texcoco have education levels that range from elementary school to postgraduate studies. This indicates that, in order to carry out this activity, a minimum education level is required in order to read, write and follow instructions for each one of the production system instructions (inputs, transformation activities, and product) [63], as well as the disposition of the farmers to learn and adopt technological innovations to make an efficient use of resources without harming the environment.

The dependence on external inputs for the production of tomatoes in greenhouses affects its sustainability, making the activity sensitive to external factors such as increases in prices and product scarcity as a result of the COVID-19 pandemic and political and military conflicts [64]. Mexico currently imports almost half of the food it consumes, along with inputs, machinery, and irrigation equipment for agricultural production, as mentioned by the 2019-2024 National Development Plan (Plan Nacional de Desarrollo 2019-2024) [65], which leads to a lack of food security and generation of technology in Mexico [18].

Measurement and water management equipment, as well as inputs for hydroponic tomato production in greenhouses in Texcoco, are imported and expensive [17], making them inaccessible for farmers in the MTL and LTL groups. This directly affects the sustainability of the production system, leading to lower WUE, yield, and profit, and therefore, a reduced possibility of acquiring and using technology. Additionally, some farmers mentioned that when fertigation equipment breaks down, it is costly and difficult for the foreign company to repair it quickly, which can increase maintenance costs and create uncertainty for the production unit. One alternative to reduce this technological dependence is to develop Mexican technology [18] through the integration of productive and governmental sectors to create technological projects for the design and construction of agricultural equipment.

Fresh water is the main input for the production of food. Out of the total water in the world, 70% is used for farming [4,5]; Mexico uses up to 76% for this purpose. Thus, the need for an efficient use of water. In this regard, produce farmers of the LTL, MTL, and HTL clusters had similar values in the WUE (0.01 kg $l^{-1}$) and they were lower than the reference values (0.04 kg $l^{-1}$) [50], which indicates an area of opportunity to improve WUE if we consider that the reference values obtained by Flores *et al.* [50] were experimental. In addition, irrigation water management is a critical issue in food security [66].

Biotic factors such as weeds, pests, and diseases are elements of the greenhouse tomato production system. However, in recent years, crop yields have increased due to the use of fertilizers and pesticides, the excessive use of which is causing problems in the environment [67,56] and in the health of people [57]. In this regard, all greenhouse tomato farmers report an incidence of weeds, pests, and diseases because many of these find favorable conditions inside the greenhouse [52], such as temperature and relative humidity. However, only a small part of LTL farmers carries out biological or organic control of pests and diseases due to the small size of their production units, and it is easy for them to prepare or purchase organic pesticides. Meanwhile, in the MTL and HTL groups with higher production surfaces in comparison with the LTL group, the use of biological or organic pesticides is not practical or attractive for them. This coincides with a report by Ortega-Martínez *et al.* [26], who found that 100% of farmers use pesticides inside greenhouses in Chignahuapan, Puebla, Mexico.

The use of technology for the control and automation of the environment inside the greenhouse, along with the production activities, is important for sustainability because it helps increase resource use efficiency. The LTL group needs access to technology for water management that allows them to be efficient in its use [66,15], as well as access to equipment for their greenhouses. Due to this, they have little possibility of controlling variables that influence their crops (temperature, relative humidity, and sunlight), since they have no measurement equipment (hygrometers, pH, or electric conductivity meters). The opposite was observed in the MTL and HTL groups, which can control greenhouse conditions and automate activities, helping them obtain higher yields than the reference value (180.32 t $ha^{-1}$) [38], as established for the economic dimension [48,66,68]. The use of technology in greenhouses not only helps increase yield and improve irrigation management but also poses a lower health risk for farmers. This coincides with Ortega *et al.* [69], who mentioned a higher exposure to pesticides in greenhouses with lower technology.

The lack of technology does not allow water and nutrients to be applied to the plants according to their demand [10,15]. LTL farmers apply water solely based on their experience, so they do not know if the plants have enough moisture to meet their evapotranspiration needs. Additionally, when preparing nutrient solutions, due to the lack of measurement equipment, they are unaware if the pH and electrical conductivity parameters are within the ranges recommended by experts for optimal plant availability [12,13]. It is a priority to provide training and demonstration workshops for this group of farmers, enabling them to learn about various technologies so they can choose the one that best fits their needs. Furthermore, farmers need to organize themselves to seek support from different government programs to acquire the technology they need to improve their productivity and sustainability. This can be done gradually, starting with measurement technologies (pH and electrical conductivity), which are less expensive (approximately 3,500 Mexican pesos).

## 5. CONCLUSION

Greenhouse tomato producers in Texcoco, Mexico, were grouped into Low, Medium, and High Technological Levels, who share cultivation management activities but do not have the same economic, environmental, social, and technological sustainability indices. The High Technological Level presents values above the reference in technology indicators for irrigation management, greenhouse equipment, and measurement equipment compared to the MTL and LTL groups. Productivity was the attribute that affected sustainability in all three groups of farmers. Fruit yield was the most important indicator. The use of technology is crucial for sustainability, but technological dependency for producing hydroponic and greenhouse tomatoes in Texcoco impacts sustainability, resulting in lower WUE, yield, and profitability. An alternative is to develop accessible Mexican technology for farmers through joint efforts from farmers, research institutions, and government agencies to design and build agricultural equipment, and to educate the key players in the system.

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## 7. LIST OF ABBREVIATIONS

| | |
|---|---|
| LTL | Low technology level |
| MTL | Medium technology level |
| HTL | High technology level |
| WUE | Water use efficiency |
| PCA | Principal components analysis |
| PC | Principal component |

## 8. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

## 9. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the international committee of medical journal editors (ICMJE) requirements/guidelines.

## 10. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

## 11. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

## 12. PUBLISHER'S NOTE

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## 13. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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