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Quality of life and sustainability

Critical points and socio-ecological dynamics of tomato (*Solanum lycopersicum* L.) cultivation in low-tech greenhouse systems in Colombia

Puntos críticos y dinámicas socioecológicas del tomate (*Solanum lycopersicum* L.) bajo cubierta en núcleos productivos colombianos

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Abstract

Tomato cultivation in Colombia must balance market demands while minimizing environmental impact. Despite productivity improvements, it still depends on external inputs such as phytosanitary products, fertilizers, and infrastructure that produce waste. Hence, the transition to sustainable cropping requires recognition of positive aspects and areas for improvement. This study aims to identify critical points in tomato cultivation under low-tech greenhouses in two different geographic regions in Colombia. The socio-ecological systems framework was adopted to promote a transition to sustainable production. The methodology considered the selection of 13 variables and 33 topics of analysis collected through the application of semi-structured interviews with key actors (32) and structured interviews with tomato producers (124). Fourteen critical points were identified across social, environmental, and productive components, categorized into: system of units and resources, governance, actors and production systems, and interactions. Notable points include ecosystem services related to water and soil provision, land tenure, technology adoption, and pollutant reduction practices. These points are crucial for driving a shift towards sustainable production in the regions studied.

Keywords: Sustainability, greenhouses, pesticides, residues, food safety, sustainable practices.

Resumen

La producción de tomate en Colombia enfrenta el reto de equilibrar las demandas de mercado y disminuir el impacto sobre los ecosistemas. Aunque la productividad del cultivo ha aumentado, la dependencia de insumos externos como productos fitosanitarios, fertilizantes e infraestructura que generan residuos sigue siendo alta, por lo que transitar hacia un sistema productivo sostenible requiere el reconocimiento de los aspectos positivos y de mejora. Por lo anterior, el objetivo de este estudio es identificar puntos críticos del cultivo de tomate bajo cubierta en dos regiones geográficas diferentes de Colombia. Para esto, se usó el enfoque del marco de sistemas socioecológicos para facilitar la transición hacia sistemas productivos sostenibles. La metodología contempló la selección de 13 variables y 33 tópicos de análisis que fueron recogidos a través de la aplicación de entrevistas semiestructuradas a actores clave (32) y estructuradas a productores (124), identificándose 14 puntos críticos de los componentes sociales, ambientales y productivos, categorizados en: sistema de unidades y recursos, gobernanza, actores y sistemas productivos, e interacciones. Se destacaron los servicios ecosistémicos de provisión de agua y suelo, la tenencia de la tierra, la adopción de tecnologías y las prácticas de reducción de contaminantes. Estos puntos son clave para impulsar un cambio hacia una producción sostenible en las regiones estudiadas.

Palabras clave: Sostenibilidad, invernaderos, plaguicidas, residuos, inocuidad, prácticas sustentables.

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1 Introduction

Food production is a constant challenge worldwide (Pérez-Vázquez et al., 2018). In Latin America, agricultural production is caught between the need to achieve the volumes and quality demanded by markets and the need to reduce impacts on ecosystems (Benton et al., 2021). Nevertheless, crop selection is largely determined by smallholder-based logic (Berdegué and Escobar, 2004), in which profitability tends to prevail over environmental considerations and over the health of both producers and consumers. This dynamic has contributed to the emergence of a market that places greater value on organoleptic characteristics than on product safety.

A clear example of this situation is tomato (*Solanum lycopersicum* L.), which ranks first worldwide in terms of production volume and second in cultivated area. China is the leading producer, with 67,636,724.8 t in 2021. In Latin America and the Caribbean, Colombia ranks fifth with a production of 875,436.86 t, after Mexico, Brazil, Argentina, and Chile (FAOSTAT, 2023).

In Colombia, tomato cultivation is carried out both in open-field conditions and under protected environments. Over the past two decades, both the cultivated area and production under protected systems have shown a steady increase, rising from 11 % in 2009 to 41.45 % in 2019. In 2022, 10,079 ha were planted under open-field conditions, with an average yield of 27 t/ha, while 7,616 ha were cultivated under protected systems, achieving an average yield of 83.74 t/ha (Agronet, 2024). The yield gap between these production systems is largely attributed to the effect of protective structures, which enhance the productive potential of the plant material (J. Jaramillo et al., 2012).

In 2022, Boyacá led protected tomato production in Colombia, with a total of 209,316 t. Although it remains among the three most productive regions, yields have stagnated in contrast to the rapid expansion of the cultivated area, which increased by 590 % over a seven-year period, reaching 2.185 ha (Agronet, 2024). Cundinamarca, ranking second, reported 869 ha under cultivation in 2022. Despite the continued expansion of cultivated areas in both regions, yields have exhibited a declining trend (Agronet, 2024).

In the ongoing global transition toward sustainable production systems (Food and Agricultural Organization, 2021), coordinated efforts among producers, technical specialists, and researchers from diverse fields of knowledge are essential. Productive systems must be understood as livelihoods embedded within the environmental, socioeconomic, and cultural dynamics of a given territory. Within this context, the objective of this study is to analyze protected tomato production systems by identifying critical points that may affect the sustainability of the production process in two of Colombia's main tomato-producing regions, using a socio-ecological systems framework. This integrative analytical approach enables the formulation of multidimensional recommendations to support sustainable production.

2 Materials and methods

2.1 Description of the study area

The study considers two regions or dynamic centres of growing greenhouse tomato production: the eastern province of Cundinamarca, in the municipalities of Cáqueza, Choachí and Fómeque; and the province of Alto Ricaurte in Boyacá, in the municipalities of Sutamarchán, Santa Sofía, Sáchica, Tinjacá and Villa de Leyva (Figure 1).

Currently, the municipalities studied produce approximately 27 % of the tomatoes harvested under protected conditions in Colombia, with 150,669 tonnes produced in the municipalities of Boyacá and 12,207 tonnes produced in the municipalities of Cundinamarca (Agronet, 2023).

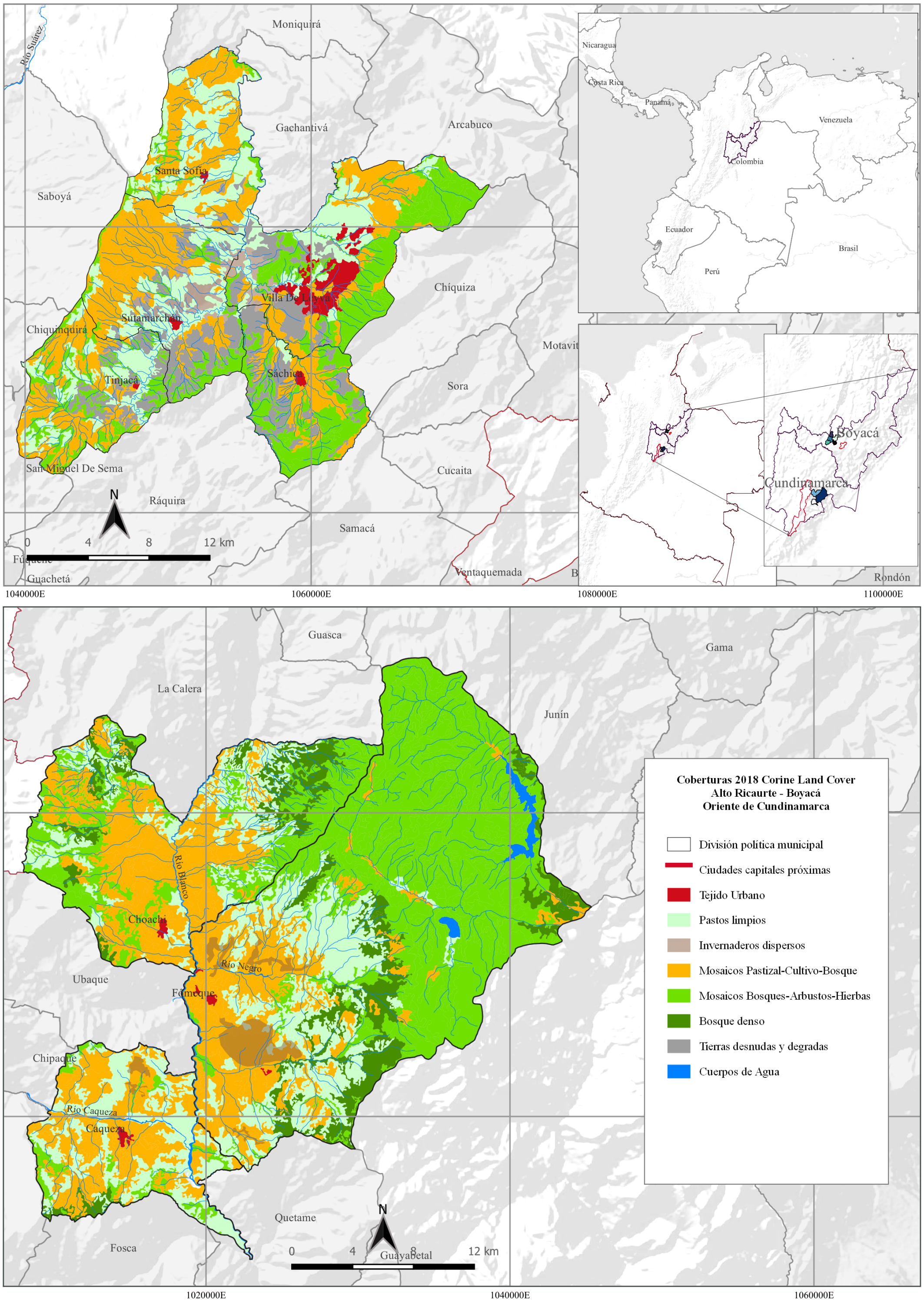

Figure 1. Location of the study area. Source: The authors, based on Corine Land Cover.

2.2 Components and variables to address the analysis of socio-ecological system

The analysis of socio-ecological systems (SES) integrates environmental and socioeconomic dimensions, allowing for a territorial understanding in which social and biophysical agents interact and provide feedback across multiple temporal and spatial scales (Ostrom, 2009).

Several theoretical approaches have been proposed to address socio-ecological analysis; however, the framework developed by McGinnis and Ostrom (2014) stands out for its clear, coherent, flexible, and context-adaptable organizational structure (Nagel and Partelow, 2022). These strengths help overcome limitations such as the complexity involved in interpreting results and the difficulty of incorporating a dynamic perspective into the variables analyzed (Hinkel et al., 2015).

In Colombia, this framework has been used primarily to address water resource management (Díaz-Pinzón et al., 2024; Gomez-Jaramillo et al., 2024), and more limitedly to analyze agroforestry food systems (Rodríguez et al., 2023) and cocoa production systems (Quiroga et al., 2024). In this sense, the present study represents an effort to advance the integration of sustainable production with socio-ecological systems analysis.

The framework disaggregates socio-ecological systems into five main components:

- **Resource system and resource units:** it describes the natural resources available within the territory.
- **Governance system:** it examines decision-making processes, including rules, norms, and land tenure arrangements.
- **Actors and production system:** it characterizes the population and productive actors within the region.
- **Interactions:** it describes the relationships among components, including existing problems and conflicts within the territory.
- **Exogenous conditions:** it addresses broader social, economic, political, and ecosystem characteristics. This component was addressed in a complementary manner through a review of secondary information.

Using the expert consultation method (Herrera-Masó et al., 2022), which is comparable to the Delphi method in terms of expert panel composition (López-Gómez, 2018), workshops and meetings were conducted in a hybrid format (virtual and in-person). The expert panel included researchers with experience in environmental, social, economic, and productive topics, with particular emphasis on soils, pests, diseases, and post-harvest processes. Through successive rounds of consensus-building, a set of variables was defined for analysis within each component. As a result, a matrix comprising 13 variables and 33 topics was consolidated (Table 1).

Based on secondary information, exogenous conditions were addressed by considering demographic trends, marginalization and poverty indices, and sustainable production policies with relevance at the territorial level.

2.3 Data Collection and Analysis

The study included the design and application of semi-structured interviews with key actors (Conagua, 2013) and structured interviews with tomato producers. These instruments were applied between December 2022 and February 2023.

The selection of key actors was based on a review of secondary information and consultations with local government offices, recognizing experience in sustainable production. Accordingly, actors involved in environmental, social, and productive processes within the region were considered. In the case of producers, fieldwork focused on rural communities historically recognized for tomato production, and farmers to be interviewed were identified in collaboration with local leaders from each region.

Table 1. Synthesis of variables included in the socio-ecological matrix.

Component	Variable	Topic
Resource System and Resource Units	Ecosystem services	SUR1. Key actors who, when consulted about ecosystem services, place greater emphasis on productive activities. SUR2. Ecosystem services most frequently highlighted by key actors. SUR3. Ecosystem services most commonly recognized by producers.
	Water resources	SUR4. Key actors who perceive water resources as scarce and water quality as moderate. SUR5. Producers who perceive that water availability during the dry season is sufficient for households and crops.
	Conservation areas	SUR6. Key actors who identify local, regional, and national conservation areas. SUR7. Producers who consider the protection of natural resources to be as important as agricultural production. SUR8. Producers who report having conservation areas within their farms.
Governance	Land size	G1. Perceptions of key actors regarding land size (productive unit) per family. G2. Average land area cultivated by producer households.
	Land tenure	G3. Perceptions of key actors regarding land tenure type. G4. Percentage of producers who identify themselves as landowners.
	Local organization	G5. Key actors who identify the presence of local organizations. G6. Producers affiliated with a local organization.
Actors and Production System	Main economic activities	A1. Main economic activities identified by key actors. A2. Key actors who perceive tomato cultivation as an important activity in the region.
	Characteristics of tomato producers	A3. Average area cultivated by households for tomato production. A4. Average age of producers. A5. Educational level of producers. A6. Household size of producers.
	Relevant characteristics of tomato cultivation	A7. Producers by type and origin of plant material. A8. Producers by type of practices associated with soil health (disinfection and fertilization). A9. Producers affected by major phytosanitary problems. A10. Producers by type of irrigation system and water source. A11. Production level and percentage of producers by type of marketing and certification.
	Main production constraints	A12. Main production constraints perceived by key actors.
Interactions	Environmental issues	I1. Main environmental problems described by key actors. I2. Producers who perceive that tomato cultivation negatively impacts the environment. I3. Main negative environmental impacts recognized by producers.
	Social issues	I4. Main social problems described by key actors.
	Sustainability-oriented practices	I5. Producers who implement at least one sustainability-oriented practice. I6. Main sustainability-oriented practices used by producers.

The designed instruments underwent expert review and were evaluated by professionals providing technical assistance for tomato cultivation in the two study regions. In addition, the structured interview format was validated with four producers (two per region). Finally, both structured and semi-structured interviews were administered in person by researchers involved in the design of the instruments, who were familiar with their objectives and capable of clarifying and expanding upon questions when necessary. This approach ensured higher response rates and the collection of reliable information for both open- and closed-ended questions.

The semi-structured interview format consisted of 16 questions, and a total of 32 interviews were conducted with key actors (16 per region), including representatives from regional government (1), local government (18), independent technical advisors (3), nursery operators (1), a project technical leader (1), producers with experience in sustainable practices (7), and a bio-input producer (1). All interviews were audio-recorded, transcribed, and consolidated for subsequent analysis.

The structured interview format included 39 questions organized into five sections. A total of 124 interviews (62 per region) were conducted using non-probabilistic convenience sampling. Data were collected in hard copy, systematized, and analyzed using descriptive statistics in Excel and multiple correspondence analysis (Johnson and Wichern, 2002).

3 Results and Discussion

At the local level, most municipalities within the study area are classified as sixth-category municipalities. This classification is based on their low population density, which does not exceed 10,000 inhabitants, and their current revenues of unrestricted allocation, which are annually below 15,000 current legal monthly minimum wages (approximately USD 5,517,441). This situation results in smaller governmental organizational structures.

At the regional scale, the study area is located within the departments of Cundinamarca and Boyacá, which are strategically connected to the national capital. According to the 2023 Departmental Competitiveness Index, these departments rank 9th and 10th, respectively, out of a total of 32 (Consejo Privado de Competitividad and SCORE-Universidad del Rosario, 2023). Both departments stand out for their progress in infrastructure, information and communication technology (ICT) adoption, education, and innovation. However, each department faces specific challenges. Boyacá must improve aspects related to the business environment, labor market, market size, and the sophistication and diversification of its economy. In contrast, Cundinamarca faces significant challenges related to environmental sustainability, public health, and the financial system.

In terms of public policy, Colombia has a robust regulatory framework that promotes sustainable agriculture, including the General Law on Agricultural and Fisheries Development (Congreso de Colombia, 1993), the National Policy on Sustainable Production and Consumption (MAVDT, 2010), and the National Circular Economy Strategy (MADS and MCIT, 2019). These instruments have guided the formulation of national and departmental government plans aimed at fostering sustainable agricultural systems. Nevertheless, Pérez (2020) emphasizes the need to strengthen coordination between the environmental and agricultural sectors to implement measures that effectively balance conservation and production, as well as to increase efforts to raise consumer awareness regarding the quality, safety, and environmental impacts of the food products they consume.

Further analysis of the remaining components identified 14 critical points, organized within the components of resource systems and resource units, governance, actors and production systems, and interactions (Figure 2).

Before analyzing the identified critical points by component, it is important to highlight that some of these points constitute feedback loops within the system, which explain the complex nature and the associated behavioral patterns of the socio-ecological system (Preiser et al., 2018). In this way, feedback loops contribute to the understanding of vicious cycles of barriers that perpetuate and hinder system performance (Hanf et al., 2025). Defining and understanding these loops supports decision-making processes (Rodriguez-Gonzalez et al., 2020), in this case aimed at advancing toward sustainable production. The feedback loops identified in the socio-ecological systems analyzed in this study are primarily related to components of actors and governance, particularly land tenure, local organization, and technological lag.

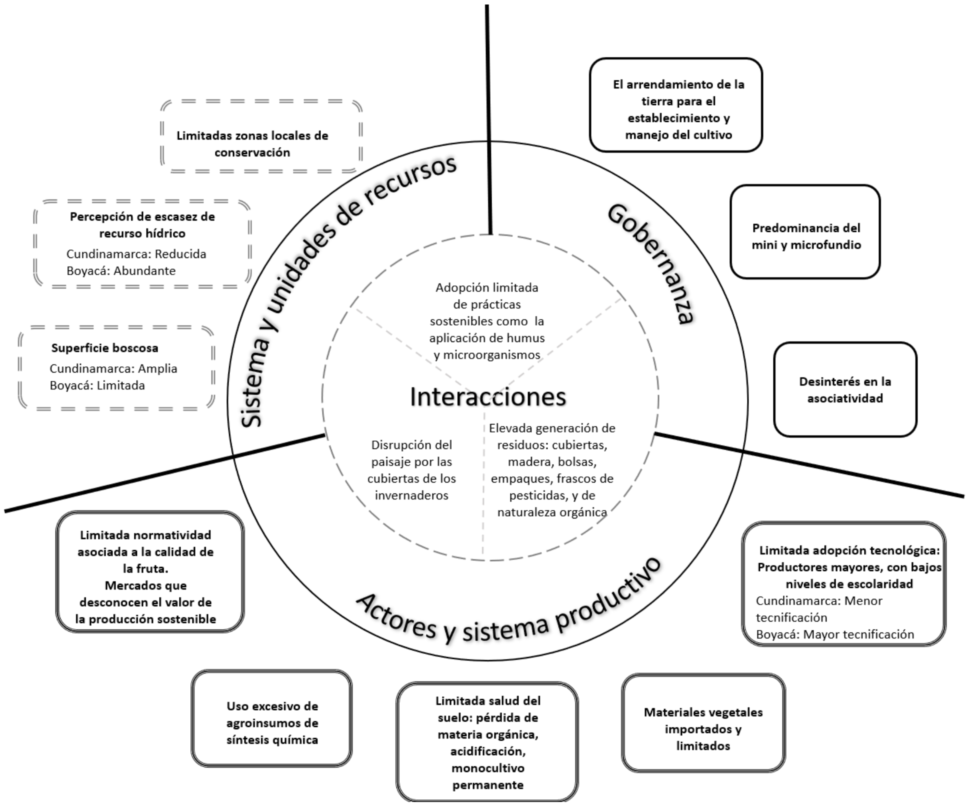

Figure 2. Synthesis of the identified critical points. Source: the authors.

3.1 Multiple Correspondence Analysis

Based on the multiple correspondence analysis, the first two dimensions explain 25.21 % of the variability of the observed data, a proportion considered adequate (Asan and Greenacre, 2008) and allow for the differentiation of three groups of producers (Figure 3).

Group 1. Sustainability-oriented producers: landowners who report no water scarcity and recognize benefits from nature such as the provision of clean air. They are aware of the negative impact of agrochemicals on human health; therefore, they incorporate sustainability-oriented practices such as the use of biofertilizers, biopesticides, and practices to protect the soil.

Group 2. Traditional agriculture producers: they rent the land and, therefore, do not own farms or conservation areas; they perceive water scarcity during the dry season and report not conducting soil analyses to support decision-making in crop management. These producers state that they are unaware of the negative effects of agrochemical use and report not using sustainability-oriented practices in their crops.

Group 3. Producers with environmental awareness and conventional management: with other forms of land tenure (they possess the land without a formal title or in partnership with other producers), they report having farms or conservation areas and perceive that water is sometimes sufficient during the dry season. They recognize ecosystem services such as water provision and the provision of food and firewood. They acknowledge that agrochemical use affects both the environment and people. Although these producers report not implementing sustainability-oriented practices, they declare conducting soil analyses in their crops for fertilization purposes.

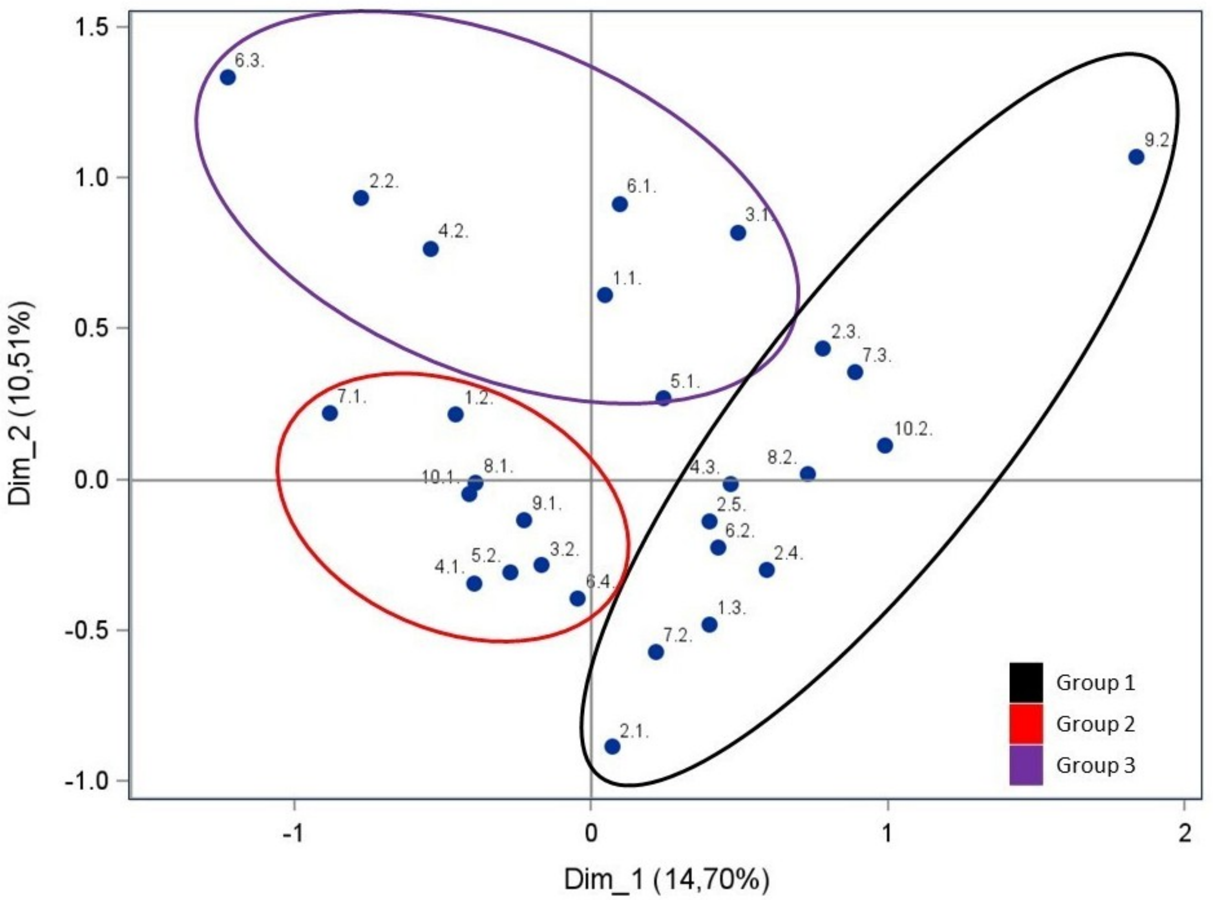

Figure 3. Multiple correspondence analysis.

Component System and resource units: 1. Water availability in summer (categories 1.1. Sometimes, 1.2. Insufficient, 1.3. Sufficient), 2. Benefits of nature (2.1. Water for domestic use and crops, 2.2. Water for domestic use and crops; food and firewood from the forest, 2.3. Water for domestic use and crops; clean air and other benefits, 2.4. Clean air, other benefits, 2.5. Other benefits), 3. Conservation areas or plots (3.1. Yes, 3.2. No). Governance: 4. Tenure (4.1. Tenant, 4.2. Other tenure, 4.3. Owner). Actors and production system: 5. Soil analysis (5.1. Yes, 5.2. No), 6. Perceived impact of agrochemicals (6.1. Yes, on the environment, 6.2. Yes, on people, 6.3. Yes, on people and the environment, 6.4. No). Interactions: 7. Applies biofertilizers (7.1. No, 7.2. Yes, one, 7.3. Yes, two or more), 8. Implements soil protection practices (8.1. No, 8.2. Yes, one or two), 9. Practices for biodiversity protection (9.1. No, 9.2. Yes, one or two), 10. Applies biopesticides (10.1. No, 10.2. Yes, one or more).

3.2 Resource system and resource units

Three critical points: forest cover, perception of water resource scarcity, and local and regional conservation areas.

Perceptions regarding water resource availability were contrasting between the two regions, as was the recognition of national conservation areas. In Boyacá, greater water scarcity is perceived, and conservation areas are more limitedly recognized, compared to Cundinamarca (Table 2).

Table 2. Results for variables of the resource system and resource units.

Variable	Topic	Boyacá	Cundinamarca
Ecosystem services	SUR1	56.2 %	12.5 %
	SUR2	– Water resource availability – Soils suitable for agriculture	– Water resource availability
	SUR3	– Water for domestic use (87 %) – Food–firewood (65 %) – Clean air (50 %)	– Water for domestic use (71 %)
Water resources	SUR4	93.8 %	25 %
	SUR5	26 %	61 %
Conservation areas	SUR6	Local or regional (37.5 %) National (6.2 %)	Local or regional (56.2 %) National (37.5 %)
	SUR7	98 %	97 %
	SUR8	35 %	48 %

In Boyacá, a low extent of stable and conserved forest area was observed, affecting strategic ecosystems. Ramos et al. (2022) reported that remaining forest patches are disappearing due to agricultural expansion. In the municipalities studied, stable forest area does not exceed 150 ha (Departamento Nacional de Planeación, 2023), representing less than 2 % of the total area.

Water scarcity has affected economic activities, highlighting the need to balance conservation and production actions. It is essential to identify conservation areas and develop restoration and land-use conversion strategies to recover forest cover.

In contrast, in Cundinamarca, municipalities contain between 3,000 and 6,000 ha of stable forest (Departamento Nacional de Planeación, 2023), representing approximately 13 % of their total area. This ensures good access to water resources and a perception of water abundance. Nevertheless, the landscape has been transformed into a mosaic of forest fragments, pastures, páramo areas, and croplands, with a trend toward decreasing conservation areas and increasing community vulnerability (Buitrago, 2022).

Multiple correspondence analysis revealed that the group implementing sustainable practices perceives lower water scarcity and recognizes additional ecosystem services, such as clean air.

The analysis of the resource system and resource units made it possible to understand both the status of natural resources essential for crop development and the relationship between producers and nature. In Boyacá, a greater impact of agricultural activity and increasingly scarce natural resources are perceived, which is related to the geographical location and productive history of each region. In this regard, the forms of interaction and use of natural resources in each region have caused different disruptions to the landscape matrix. This is particularly evident in Boyacá, where the rural landscape has been modified by greenhouse structures, reducing its visual appeal and negatively affecting tourism in internationally recognized areas such as the Villa de Leyva Valley. This situation, along with the perception of water scarcity, underscores the need to transition toward sustainable production systems. In contrast, Cundinamarca, due to greater water availability and the resulting higher forest cover, does not exhibit such a pronounced impact on the landscape.

3.3 Governance

Three critical points: predominance of private property and smallholdings in both regions; as well as limited participation in local organizations (Table 3).

Table 3. Variable governance outcomes.

Variable	Topic	Boyacá	Cundinamarca
Land size	G1	1–5 ha	
	G2	2.6 ha	1.6 ha
Land tenure	G3	Landowners (with possession certificates or documents accrediting inheritance)	
	G4	41 %	55 %
Local organization	G5	56.2 %	68.8 %
	G6	11.3 %	5 %

One aspect that increases the vulnerability of tomato-producing communities and threatens system stability is the low organizational capacity of producers. Individual interests hinder collective action, which, according to Escobedo (2018), also affects other value chains such as coffee. This highlights the need for cooperation, commitment, and information flow under a win–win perspective; otherwise, the system fails due to insufficient empirical knowledge and a lack of organization (Vargas-Hernández, 2013).

Protected tomato production is intensive and small-scale, which has implications for sustainability. Gamboa et al. (2020) report an inverse relationship between sustainability and farm size. The small size of production units limits the conservation of vegetation, as productive land use is prioritized. In addition, multiple correspondence analysis shows that landowners implement more sustainable practices than tenants.

This finding is particularly relevant in Colombia, which has a land ownership Gini coefficient of 0.897 (Alzate, 2020), the third highest in Latin America, where land is concentrated in the hands of few owners while many producers are tenants. The latter do not perceive the consequences of land use beyond economic interest, underscoring the need to strengthen their environmental awareness.

The analysis of the governance component revealed strong similarities between the two study regions in terms of land tenure under private ownership, the predominance of smallholdings, and limited organizational capacity. These aspects should inform the design of sustainable production proposals for the region and are also linked to the fact that these two regions together concentrate 25 % of the country's population.

3.4 Actors and Production System

Five critical points were identified: low adoption of technologies, reliance on imported plant material, limited soil health, excessive use of agro-inputs, and regulatory and market lag with an emphasis on food safety (Table 4).

Interviewees in Boyacá and Cundinamarca identified horticulture and livestock production as the main economic activities, highlighting the relevance of tomato cultivation. In Boyacá, producers have an average age of 49 years; 37.1 % completed primary education, while 19.4 % did not complete it; and an average of 0.89 ha of their production unit is dedicated to tomato cultivation. In Cundinamarca, the average age of producers is 47 years; 47.5 % completed primary education and 23 % did not complete it; and 1.4 ha are dedicated to tomato production. Households in both regions consist of 3 to 4 members (Table 4).

Among the main problems associated with tomato cultivation in Boyacá, high infrastructure costs (greenhouse structures and irrigation systems) and agro-inputs stand out (56.2 %), followed by the impact of pests and diseases (37.5 %) and difficulties related to marketing and market access (37.5 %). In Cundinamarca, the most prominent issues are the impact of pests and diseases (43.8 %) and inadequate soil and water management (43.8 %).

Table 4. Results for the variable: Characteristics of tomato cultivation.

Topic	Subtopic	Boyacá	Cundinamarca
A7	Chonto type[1]	90 %	95 %
	Long-life type[2]	10 %	5 %
	It comes from a nursery	92 %	88.8 %
A8	Fertilization based on soil analysis	56.9 %	56.4 %
	Soil disinfection using chemical products	83.9 %	67.7 %
	Application of organic matter to the soil	16.1 %	50 %
	Applies chemical fertilizers	100 %	100 %
A9	Most frequently reported phytosanitary problems	– Tomato leafminer (*Tuta absoluta*) (53 %) – Whitefly (*Trialeurodes vaporariorum*) (52 %) – Gray mold (*Botrytis cinerea*) (31 %)	– Fusarium (*Fusarium oxysporum* f. sp. *lycopersici*) (32 %) – Gall midge (*Prodiplosis longifila*) (23 %) – Tomato leafminer (*Tuta absoluta*) (21 %)
A10	Drip irrigation	100 %	95.1 %
	Main water source for irrigation	Reservoirs: 60.8 % Springs and streams: 39.2 %	Reservoirs: 35.4 % Springs and streams: 64.6 %
A11	Average production (t/ha/year)	51	32
	Certification in Good Agricultural Practices	1.6 %	0 %
	Sales agreement with the buyer[3]	72.6 %	83.7 %

[1] Type of tomato used for stew preparation.
[2] Type of tomato used for salad preparation.
[3] Formal and informal agreements between the producer and the intermediary for crop sales.

Of the five critical points identified, the first is related to the limited adoption of technology. Producers face difficulties in accessing reliable information and training on technologies for protected agriculture. In addition, adherence to traditional production models generates resistance to change, limiting improvements and maintaining dependence on obsolete technologies.

Cachipuendo et al. (2025), in the Ecuadorian context, note that low levels of agricultural technification restrict the appropriate use of water. This limitation is associated with low-efficiency infrastructure, poor maintenance, and the absence of measurement instruments that allow for rational control of water resources. The authors emphasize that the lack of technological innovation, together with traditional community-based irrigation management, reduces adaptive capacity to climate variability and compromises long-term crop sustainability.

Socioeconomic characteristics such as age and educational level influence crop productivity. Cano et al. (2016) indicate that higher levels of education are associated with greater productivity, whereas increasing age tends to reduce it, possibly due to limited adoption of technological innovations offered by associations, producer organizations, and scientific institutions. In Colombia, various institutions provide socially relevant knowledge; however, efforts and approaches are often duplicated, resulting in fragmented and sometimes divergent perspectives.

In terms of age structure, neither integration nor generational renewal is observed. In Colombia, as in other Latin American countries, family farming is dominated by an aging male labor force (70 %). This is largely due to youth migration to urban areas driven by a lack of opportunities in rural zones, which negatively affects regional economies by reducing labor availability and lowering the productivity of traditional crops (López et al., 2018), thereby placing the sustainability of tomato cultivation within the family age structure at risk.

This technological lag is also reflected in crop yields. Average production reaches 51 t/ha/year in Boyacá and 32 t/ha/year in Cundinamarca. With a national average yield of 46.6 t/ha/year, Colombia ranks 59th globally, compared to yields exceeding 300 t/ha/year in countries such as the Netherlands, Belgium, Sweden, Finland, Denmark, Ireland, and the United Kingdom (FAOSTAT, 2023). This indicates the existence of a technological gap in Colombia but also represents an opportunity to develop or adapt technologies that enhance national production.

The second critical point of this component is related to the fact that, although Colombia is the center of origin of tomato (Délices et al., 2019), the cultivars currently grown have been improved in the United States and Europe, whose breeding companies supply the seeds used in the country. However, the demand for materials more resistant to phytosanitary problems such as *Fusarium* has led to the adoption of techniques such as grafting in nurseries, combining tolerant rootstocks with high-yield hybrids such as Libertador and Roble. This practice has increased the cost of seedlings for tomato producers. Furthermore, the high demand for fresh tomato limits varietal diversity, constraining sustainable production strategies in local markets with specific uses (Ríos et al., 2014).

The third critical point highlights challenges associated with soil health:

- **Loss of organic matter:** The lack of practices that promote its retention and increase, such as the use of cover crops, limits improvements in organic matter content. Promoting such practices would reduce erosion risk and enhance microbial activity. However, they are not commonly implemented, as producers often relocate production sites when soil degradation negatively affects yields (Cuellas et al., 2019).
- **Soil acidification:** This phenomenon affects nutrient availability, thereby impacting crop quality and yield. The controlled application of liming amendments can counteract acidification and restore optimal pH levels (Dikinya and Mufwanzala, 2010).
- **Lack of crop rotation:** Continuous monocropping of tomato depletes specific nutrients and increases vulnerability to phytopathogens and insect pests. Implementing rotation plans with complementary species can restore soil biodiversity and reduce pressure on particular nutrients (Díaz et al., 2004).

The fourth critical point concerns the use of agro-inputs, which accounts for 64 % of direct production costs. Dependence on chemically synthesized products for pest and disease control reflects a constant need for external inputs to maintain crop health and productivity. Frequent pesticide use generates environmental and socioeconomic impacts (Valentín et al., 2021), while ecological imbalance favors pests that displace beneficial organisms, forcing more intensive management practices that compromise fruit safety (Caro and Cortés, 2020).

A sustainable vision of tomato production should adopt integrated pest and disease management with a preventive approach, using organomineral inputs, biological control, traps, and allelopathic strategies to reduce dependence on chemical inputs. Residue studies have reported high application levels of insecticides such as chlorpyrifos, with concentrations exceeding the maximum residue limits (MRLs) established by the European Union (> 0.1 ppm) (Guerrero, 2003).

Patiño et al. (2020) identified pesticide residues such as diflubenzuron and methamidophos at concentrations above established MRLs. This finding is consistent with the perceptions of interviewees, who reported high pressure from pests such as whitefly (*Trialeurodes vaporariorum*), gall midge (*Prodiplosis longifila*), and tomato leafminer (*Tuta absoluta*), whose management relies primarily on periodic applications of chemical insecticides.

These elements lead to the fifth critical point of this component: limited progress in the development and implementation of regulations associated with fruit quality. In 2014, Colombia promoted the "National Phytosanitary and Food Safety Policy" to implement a "National Pesticide Residue Plan"; however, it was not until 2022 that the Colombian Agricultural Institute (ICA) initiated national residue monitoring, and the results have yet to be published (Instituto Colombiano Agropecuario, 2022).

Advancing toward sustainable production is closely linked to regulation, pricing, and markets (Codron et al., 2014; Rodríguez-Robayo et al., 2022). Regulatory frameworks are still under development, and the main market is the Bogotá Central Wholesale Market, where certifications are not required, food safety is not inspected, and the environmental impact of production processes is not considered. This explains why only one of the 124 interviewed producers holds certification in Good Agricultural Practices, highlighting the need for markets that value sustainable production.

The analysis of the actors and production system component revealed significant similarities between the two study regions. Although Boyacá exhibits slightly greater technological innovation than Cundinamarca, a clear technological lag persists in both regions. Other topics in both Boyacá and Cundinamarca highlight the urgent need to address soil health, promote crop monitoring, and implement practices that avoid calendar-based agrochemical applications. Likewise, the importance of reflecting on tomato food safety issues in both regions was evident, particularly in terms of creating incentives for production under non-conventional and more sustainable production schemes.

3.5 Interactions

Three critical points were identified: greenhouse infrastructure and its management, which generate significant waste and impact the landscape, as well as progress in the adoption of sustainability-oriented practices (Table 5).

Innovations in protected agriculture, tradition and a lack of investment limit the adoption of technological improvements that could enhance efficiency and productivity. Moreover, the tomato marketing model does not provide sufficient returns to justify technological investment within the production system.

There is a marked disparity in the level of technification between the Boyacá and Cundinamarca clusters. Farmers in Cundinamarca rely more heavily on traditional and less-technified methods based on empirical knowledge. This situation is largely due to limited access to advanced technologies and insufficient training in greenhouse practices. In contrast, Boyacá has exhibited a higher level of technification, particularly in fertigation systems (Villagran and Bojacá, 2021).

This difference may be explained by better infrastructure and easier access to farms and greenhouses in Boyacá. In Cundinamarca, however, road conditions hinder access to production units, a problem exacerbated by the region's topography and climate (Villagran and Bojacá, 2021).

In both clusters, greenhouse covers adapted from the floriculture sector have been used since the 1970s. Although these structures have increased tomato production, challenges remain in optimizing crop development (Villagran et al., 2021). One of the main challenges is the implementation of structures better adapted to local climatic conditions, with greater microclimatic control and improved alignment with the ecophysiological demands of the crop, which would enhance resource-use efficiency (Rocha et al., 2021).
However, greenhouse use generates waste at the end of the materials' life cycle. The main environmental issue associated with greenhouse tomato production is the generation of solid waste, including plastic covers, wood, bags, packaging, pesticide containers, as well as organic residues.

Tomato losses during production, transport, storage, and consumption generate significant waste. According to Martínez and Quintero (2017), postharvest vegetable losses in Colombia reach 7 %. Of the 162,876 t of tomatoes produced in 2022 in the municipalities of Boyacá and Cundinamarca (Agronet, 2023), an estimated 11,401 t were lost.

Furthermore, the ecosystem service related to landscape aesthetics was not widely recognized. Greenhouse tomato cultivation alters the landscape and disrupts the ecological matrix. This effect is particularly evident in Boyacá, especially in Villa de Leyva, a globally recognized tourist area known for its desert landscapes, páramo ecosystems, lagoons, and valleys (Ramos et al., 2022). Greenhouse structures have modified the landscape, affecting tourism, which has pointed to the high visibility of greenhouses and their visual impact (Figure 4).

Table 5. Results for interaction variables.

Variable	Topic	Boyacá	Cundinamarca
Environmental issues	I1	– General impact of agricultural activities (50 %) – High use of agrochemicals (37.5 %) – Contamination of water sources (37.5 %) – Increase in greenhouse structures and poor waste management (31.2 %)	– General impact of agricultural activities (50 %) – High use of agrochemicals (37.5 %)
	I2	71 %	21 %
	I3	– High plastic use (30.6 %) – Landslides and soil erosion (21 %) – High use of agrochemicals (19.4 %)	– High use of agrochemicals (14.5 %) – Landslides and soil erosion (9.7 %)
Social issues	I4	– Youth migration and labor shortages (56.2 %) – Arrival of foreign migrants (31.2 %) – Insecurity, theft, and extortion (31.2 %)	– Youth migration and labor shortages (37.5 %)
Practices oriented towards sustainability	I5	79 %	90 %
	I6	– Incorporation of liquid humus into the soil (32.3 %) – Crop rotation (52.2 %) – Garlic–chili preparation as a biopesticide (31.3 %)	– Incorporation of liquid humus into the soil (77.4 %) – Commercial microorganisms (24.2 %) – Crop rotation (89.3 %) – Garlic–chili preparation as a biopesticide (41.4 %)

This impact is less pronounced in Cundinamarca, possibly because it is a less tourism-oriented region compared to Boyacá, as well as due to the dispersion of greenhouses and the rugged topography of the area.

At the level of identity, the landscape in both areas is perceived as an influential, unifying, and characteristic factor that shapes local idiosyncrasy. The landscape is valued as a competitive advantage for nature-based destinations, as noted by Clark et al. (2026), where the natural environment becomes a demanding factor for enterprises that must operate within sustainability thresholds. In this regard, Olwig (2002) emphasizes that natural landscapes evolve into cultural landscapes, in which geographical and ecological characteristics are integrated with human modifications, including built structures and land use (Cosgrove, 2008). However, in the study area, tensions have emerged associated with disruptions of the landscape matrix, fostering struggles for the conservation of natural landscape symbols and motivating producers' interest in transitioning toward sustainability.

In tomato cultivation, the adoption of agroecological practices (Wezel et al., 2009) promoted under tropical agriculture models (C. Jaramillo, 2019) can be identified. The regional approach seeks to replace chemical inputs with organo-mineral and biological sources. However, tomato producers continue to prefer chemical control for managing phytosanitary problems, despite promising experiences reported by those who use biopreparations, who indicate positive effects and reduced management costs.

Figure 4. Landscape change due to the presence of greenhouses for tomato production, Sutamarchán, Boyacá. Photograph: Diego Fernando Sánchez Vivas.

According to Tittonell (2019), agroecological transitions are multiscalar and multidimensional, and in tomato cultivation they remain incipient. Exogenous factors, such as the post-pandemic increase in chemical agro-input prices and the influence of environmental stakeholders, have fostered collective awareness of the risks associated with synthetic pesticides and have promoted agroecological practices (Torres-Carral, 2021).

Finally, another driving factor is the recognition of positive experiences in alternative management. Studies on organic matter sources, microorganism-based bioproducts, and agroecological management of greenhouse tomatoes report encouraging results, supporting the transition toward sustainable production models.

The analysis of the interactions component revealed a greater impact of tomato cultivation in Boyacá compared to Cundinamarca, mainly attributable to the productive trajectory of each region. In Boyacá, tomato cultivation has approximately 25 years of development, whereas in Cundinamarca the system has been implemented for about 17 years. Nevertheless, progress in the adoption of sustainable practices in both regions remains limited and has focused primarily on the use of bioproducts or biopreparations, largely driven by rising agrochemical prices.

4 Conclusions

Based on the 13 variables and 33 topics used in the socio-ecological analysis of protected tomato cultivation in the departments of Boyacá and Cundinamarca, 14 critical points affecting the production process were identified. In this way, the application of the socio-ecological systems framework is expanded to sustainable production, moving beyond its traditional use in analyzing conservation actions for natural resource management.

The two tomato-producing regions analyzed exhibit multiple similarities in social aspects and crop management practices. However, geographical and historical differences are decisive in explaining the contrasts observed in the resource system and resource components and in interactions. Boyacá, characterized by drier conditions and a longer trajectory in tomato production, has experienced greater incorporation of technological innovations over time. Nevertheless, this intensification has generated a more evident impact on the landscape and available natural resources.

Across both regions, the resource system and resource units component revealed the absence or lack of awareness of local conservation areas. In the governance component, private land ownership under smallholdings predominated, along with widespread disinterest among producers in consolidating and participating in local organizations. The actors and production system component showed that tomato cultivation is characterized by excessive use of chemically synthesized agro-inputs, loss of organic matter, permanent monocropping, and soil acidification, resulting in limited soil health. Finally, the interactions component reflected limited adoption of sustainable practices in tomato cultivation, together with high waste generation and abrupt landscape changes due to the expansion of greenhouse covers across the territory.

These findings suggest the need to focus efforts on: (a) strengthening local and regional conservation actions to ensure that water resources are maintained in Cundinamarca and not depleted in Boyacá; (b) fostering environmental awareness and social capital among smallholder tomato-producing families; (c) designing and implementing technologies that promote sustainable production, protect essential resources such as soil and water, reduce environmental impacts, and ensure greater food safety; (d) promoting the use of local materials in infrastructure, planting, and crop management to reduce dependence on external inputs; and (e) identifying and developing markets that value sustainable production, as the added value of differentiated production is currently not fully recognized.

It is recommended that future research apply the socio-ecological systems framework to the analysis of sustainable production deepen, through participatory approaches, the understanding of feedback loops that determine the main barriers to transitioning toward sustainability. This would support the definition of joint strategies among local, regional, and national actors to advance the consolidation of sustainable and resilient territories. Likewise, further research should explore cultural ecosystem services, beyond landscape aesthetics, to capture elements such as sense of belonging, identity, and connection with nature, among others.

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References

Agronet. (2023). *Base agrícola EVA de 2019 a 2022.* Online: https://n9.cl/3p5a2

Agronet. (2024). *Reporte: Área, producción y rendimiento nacional por cultivo.* Online: https://n9.cl/dhvg

Alzate, D. (2020). Concentración de la tierra y las zonas de interés de desarrollo rural, económico y social (Zidres) en los montes de maría. maría la baja y carmen de bolívar. *Prolegómenos*, *23*(46), 51–70. Online: https://doi.org/10.18359/prole.4309.x

Asan, Z., and Greenacre, M. (2008). Measures of fit in multiple correspondence analysis of crisp and fuzzy coded data. Online: http://dx.doi.org/10.2139/ssrn.1107815

Benton, T., Bieg, C., Harwatt, H., Pudassaini, R., and Wellesley, L. (2021). *Food system impacts on biodiversity loss: Three levers for food system transformation in support of nature*. London, UK: Chatham House. Online: https://n9.cl/mw42do

Berdegué, J. A., and Escobar, G. (2004). *Tecnología y pobreza: opciones para FONTAGRO* (Inf. Téc. n.º A50/6609). Washington, USA: Fondo Regional de Tecnología Agropecuaria. Online: https://n9.cl/hqrny

Buitrago, P. (2022). *Pérdida de bosque alto andino por procesos de paramización y cambio climático en ecosistemas de alta montaña.* Online: https://n9.cl/izq4q

Cachipuendo, C., Ilbay, M., and Requelme, N. (2025). Gestión comunitaria y sostenibilidad en sistemas de riego andinos mediante indicadores de uso eficiente del agua en la agricultura. *La Granja: Revista de Ciencias de la Vida*, *42*(2), 41–60. Online: https://doi.org/10.17163/lgr.n42.2025.03

Cano, S., Iregui, B., Ramírez, G., and Tribín, U. (2016). *El desarrollo equitativo, competitivo y sostenible del sector agropecuario en colombia*. Banco de la República. Online: https://n9.cl/105td

Caro, L., and Cortés, P. (2020). *Estado del arte de los efectos de plaguicidas de uso agrícola para la salud y el ambiente en colombia (2007-2019)* (Inf. Téc.). Online: https://n9.cl/0dzrf

Clark, C. D., Matarrita-Cascante, D., Tkatch, J. R. V., and Fariha, M. S. (2026). Examining the competitive advantage of nature-based destinations: Applying a holistic resource-based theory framework. *Tourism Management*, *112*, 105281. Online: https://doi.org/10.1016/j.tourman.2025.105281

Codron, J. M., Adanacioğlu, H., Aubert, M., Bouhsina, Z., El Mekki, A., Rousset, S., . . . Yercan, M. (2014). The role of market forces and food safety institutions in the adoption of sustainable farming practices: The case of the fresh tomato export sector in morocco and turkey. *Food Policy*, *49*(1), 268–280. Online: https://doi.org/10.1016/j.foodpol.2014.09.006

Conagua. (2013). *Guía de identificación de actores clave. serie: Planeación hidráulica en méxico* (Inf. Téc.). Ciudad de México: Semarnat. Online: https://n9.cl/hyudia

Congreso de Colombia. (1993). *Ley 101 de 1993. ley general de desarrollo agropecuario y pesquero.* Online: https://n9.cl/nmiwe (Colombia)

Consejo Privado de Competitividad, and SCORE-Universidad del Rosario. (2023). *Índice departamental de competitividad 2023* (Inf. Téc.). Punto Aparte editores. Online: https://n9.cl/vm0a90

Cosgrove, D. (2008). *Geography and vision: Seeing, imagining and representing the world*. London & New York: I.B. Tauris. Online: https://n9.cl/ln2vz

Cuellas, M., Amoia, P., and Delmazzo, P. (2019). Efecto de diferentes tratamientos de desinfección del suelo sobre las propiedades edáficas. *Chilean Journal of Agricultural & Animal Sciences*, *35*(1), 26–37. Online: https://doi.org/10.4067/S0719-38902019005000103

Departamento Nacional de Planeación. (2023). *Terridata.* DNP. Online: https://n9.cl/6ghncx

Dikinya, O., and Mufwanzala, M. (2010). Chicken manure-enhanced soil fertility and productivity: Effects of application rates. *Journal of Soil Science and Environmental Management*, *1*(3), 46–54. Online: https://n9.cl/hmstw6

Délices, G., Ovalle, O., Mota-Vargas, C., Pastrana, R., Pastrana, R., Meza, P., and Serna-Lagunes, R. (2019). Biogeography of tomato solanum lycopersicum var. cerasiform (solanaceae) in its center of origin (south america) and domestication (mexico). *Revista de Biología Tropical*, *67*(4), 1023–1036. Online: https://doi.org/10.15517/rbt.v67i4.33754

Díaz, G., Hernández, T., and Cabello, R. (2004). Reseña bibliográfica de la rotación de cultivos, un camino a la sostenibilidad de la producción arrocera. *Cultivos Tropicales*, *25*(3), 19–44. Online: https://n9.cl/p8yh

Díaz-Pinzón, L., Sierra, L., Trillas, F., and Verd, J. (2024). The social-ecological system framework of urban wetlands: The role of collective management at local level. *International Journal of the Commons*, *18*(1), 649–669. Online: https://doi.org/10.5334/ijc.1399

Escobedo, A. (2018). *Cadena de valor de café de guatemala* (Inf. Téc.). CATIE. Online: https://doi.org/10.13140/RG.2.2.32152.65282

FAOSTAT. (2023). *Crops and livestock products.* FAO. Online: https://n9.cl/7wq46

Food and Agricultural Organization. (2021). *Experiencias de transición agroecológica en colombia* (Inf. Téc.). Bogotá: Sembrando Capacidades (Cooperación Brasil-Colombia-FAO). Online: https://n9.cl/8yhif

Gamboa, C., Bojacá, C., Schrevens, E., and Martens, M. (2020). Sustainability of smallholder quinoa production in the peruvian andes. *Journal of Cleaner Production*, *264*, 121657. Online: https://doi.org/10.1016/j.jclepro.2020.121657

Gomez-Jaramillo, Y., Berrouet, L., Villegas-Palacio, C., and Berrio-Giraldo, L. (2024). Navigating water security: A sustainability evaluation in basin socio-ecological systems. the grande river basin case study, antioquia-colombia. *Science of The Total Environment*, *959*(10), 178354. Online: https://doi.org/10.1016/j.scitotenv.2024.178354

Guerrero, J. (2003). Estudio de residuos de plaguicidas en frutas y hortalizas en áreas específicas de colombia. *Agronomía Colombiana*, *21*, 198–209. Online: https://n9.cl/pix9x

Hanf, F., Ament, F., Boettcher, M., Burgemeister, F., Gaslikova, L., Hoffmann, P., . . . Wicke, M. (2025). Towards a socio-ecological system understanding of urban flood risk and barriers to climate change adaptation using causal loop diagrams. *International Journal of Urban Sustainable Development*, *17*(1), 69–102. Online: https://doi.org/10.1080/19463138.2025.2474399

Herrera-Masó, J., Calero, J., González, M., Collazo, M., and Travieso, Y. (2022). El método de consulta a expertos en tres niveles de validación. *Revista Habanera de Ciencias Médicas*, *21*(1), e4711. Online: https://n9.cl/pc81f

Hinkel, J., Cox, M., Schulter, M., Binder, C., and Falk, T. (2015). A diagnostic procedure for applying the social-ecological systems framework in diverse cases. *Ecology and Society*, *20*(1), 32. Online: https://doi.org/10.5751/ES-07023-200132

Instituto Colombiano Agropecuario. (2022). *Plan de monitoreo de residuos de plaguicidas químicos en especies vegetales en colombia.* Online: https://n9.cl/f23dt (ICA)

Jaramillo, C. (2019). *Programa de formación continua especializada: Producción agroecológica de frutas y hortalizas* (Inf. Téc.). Corpocyt, Ed. and Asohofrucol. Online: https://n9.cl/2eokr

Jaramillo, J., Sánchez-León, G., Rodríguez, V., Aguilar, P., Gil, L., Hío, J., . . . Guzmán-Arroyave, M. (2012). *Tecnología para el cultivo de tomate bajo condiciones protegidas*. Bogotá: Corpoica. Online: https://n9.cl/uqj1n

Johnson, R., and Wichern, D. (2002). *Applied multivariate statistical analysis* (6th ed.). Pearson Modern Classics. Online: https://n9.cl/6hnmk

López, E., Martínez, L., Martínez-Cañas, C., and Vargas-Prieto, A. (2018). Desarrollo rural y envejecimiento: caso de estudio municipio de chinavita, boyacá, colombia. *Revista investigación y desarrollo e innovación*, *8*(2), 193–206. Online: https://doi.org/10.19053/20278306.v8.n2.2018.7959

López-Gómez, E. (2018). El método delphi en la investigación actual en educación: una revisión teórica y metodológica. *Educación XX1*, *21*(1), 17–40. Online: https://doi.org/10.5944/educXX1.15536

MADS, and MCIT. (2019). *Estrategia nacional de economía circular. cierre de ciclos de materiales, innovación tecnológica, colaboración y nuevos modelos de negocio* (Inf. Téc.). Bogotá D.C., Colombia: Ministerio de Ambiente y Desarrollo Sostenible and Ministerio de Comercio, Industria y Turismo. Online: https://n9.cl/jx6lxm

Martínez, M., and Quintero, J. (2017). Estado actual de los desperdicios de frutas y verduras en colombia. En *Memorias 4to congreso internacional* *amitic* (Vol. 1, pp. 194–201). Portal de Revistas Académicas Universidad Tecnológica de Panamá UTP. Online: https://n9.cl/dbzmi3

MAVDT. (2010). *Política nacional de producción y consumo sostenible* (Inf. Téc.). Bogotá: Ministerio de Ambiente, Vivienda y Desarrollo Territorial. Online: https://n9.cl/oo2if

McGinnis, M., and Ostrom, E. (2014). Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society*, *19*(2), 1–30. Online: https://doi.org/10.5751/ES-06387-190230

Nagel, B., and Partelow, S. (2022). A methodological guide for applying the social-ecological system (SES) framework: a review of quantitative approaches. *Ecology and Society*, *27*(4), 1–39. Online: https://doi.org/10.5751/ES-13493-270439

Olwig, K. (2002). *Landscape, nature and the body politic: From britain's renaissance to america's new world*. Madison, WI: University of Wisconsin Press. Online: https://doi.org/10.1080/00291950310003043

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(5939), 419–422. Online: https://doi.org/10.1126/science.1172133

Patiño, M., Valencia-Guerrero, M., Barbosa-Ángel, E., Martínez-Cordón, M., and Donado-Godoy, P. (2020). Evaluation of chemical and microbiological contaminants in fresh fruits and vegetables from peasant markets in cundinamarca, colombia. *Journal of Food Protection*, *83*, 1726–1737. Online: https://doi.org/10.4315/0362-028X/JFP-19-453

Preiser, R., Biggs, R., De Vos, A., and Folke, C. (2018). Social-ecological systems as complex adaptive systems: organizing principles for advancing research methods and approaches. *Ecology and Society*, *23*(4), 46. Online: https://doi.org/10.5751/ES-10558-230446

Pérez, M. (2020). Retos de la política ambiental colombiana frente a los desafíos de la OCDE y ODS. *Análisis político*, *33*(99). Online: https://doi.org/10.15446/anpol.v33n99.90970 (Mayo-Agosto)

Pérez-Vázquez, A., Leyva, D., and Gómez, F. (2018). Desafíos y propuestas para lograr la seguridad alimentaria hacia el año 2050. *Revista Mexicana de Ciencias Agrícolas*, *9*(1), 175–189. Online: https://doi.org/10.29312/remexca.v9i1.857

Quiroga, S., Suárez, C., Hernanz, V., Aguiño, J., and Fernández-Manjarrés, J. (2024). Analysing post-conflict policies to enhance socio-ecological restoration among black communities in southern colombia: Cacao cropping as a win–win strategy. *Forest Policy and Economics*, *163*, 103198. Online: https://doi.org/10.1016/j.forpol.2024.103198

Ramos, A., Alvarado, A., Montenegro, L., and Sandoval, A. (2022). Oportunidades de conservación del paisaje rural andino en el suroccidente de tunja, boyacá (colombia). *Revista Mutis*, *12*(2). Online: https://doi.org/10.21789/22561498.1823

Rocha, G., Pichimata, M., and Villagran, E. (2021). Research on the microclimate of protected agriculture structures using numerical simulation tools: a technical and bibliometric analysis as a contribution to the sustainability of under-cover cropping in tropical and subtropical countries. *Sustainability*, *13*(18), 10433. Online: https://doi.org/10.3390/SU131810433

Rodriguez-Gonzalez, P., Rico-Martinez, R., and Rico-Ramirez, V. (2020). Effect of feedback loops on the sustainability and resilience of human-ecosystems. *Ecological Modelling*, *426*. Online: https://doi.org/10.1016/j.ecolmodel.2020.109018

Rodríguez, T., Reu, B., Bolívar-Santamaría, S., Cortés-Aguilar, A., and Buendía, C. (2023). A framework for participatory scenario planning to guide transitions towards sustainability in mountain social-ecological systems: A case study from the colombian andes. *Land Use Policy*, *132*, 106817. Online: https://doi.org/10.1016/j.landusepol.2023.106817

Rodríguez-Robayo, K., Pulido-Blanco, V., Rojas-Ramírez, D., and Martínez-Camelo, F. (2022). Buenas prácticas agrícolas y sostenibilidad del cultivo de cebolla de rama (Allium fistulosum L.) en la cuenca del lago de tota (boyacá, colombia). *Revista Agroalimentaria*, *28*(2407-2022-909), 139–169. Online: https://n9.cl/ivo4q

Ríos, O., Chávez, J., and Carrillo, J. (2014). Producción tradicional y diversidad de tomate (Solanum lycopersicum L.) nativo: un estudio de caso en tehuantepec-juchitán, méxico. *Agricultura Sociedad y Desarrollo*, *11*(1), 35–5. Online: https://n9.cl/pgdegn

Tittonell, P. (2019). Las transiciones agroecológicas: múltiples escalas, niveles y desafíos. *Revista de la Facultad de Ciencias Agrarias de la Universidad Nacional del Cuyo*, *51*(1), 231–246. Online: https://n9.cl/p49jpl

Torres-Carral, G. (2021). Acerca del concepto de socioecosistema. un análisis eco-social. *Textual*, *77*, 89–114. Online: https://doi.org/10.5154/r.textual.2021.77.03

Valentín, A., Guerrero, A., and Condori, L. (2021). Identificación de residuos de contaminantes químicos en tomate para determinar su grado de toxicidad. *Journal Boliviano de Ciencias*, *17*(Especial), 38–52. Online: https://doi.org/10.52428/20758944.v17iespecial.5

Vargas-Hernández, J. (2013). La teoría de recursos y capacidades y el emprendimiento: caso de una microempresa agropecuaria rural. *Voxpopuli*(12), 81–88. Online: https://n9.cl/qyan5

Villagran, E., and Bojacá, C. (2021). Three-dimensional numerical simulation of the thermal and aerodynamic behavior of a roof structure built on a slope and used for horticultural production. *Comunicata Scientiae*, *12*, e3593. Online: https://n9.cl/ayxkgs

Villagran, E., Bojacá, C., and Akrami, M. (2021). Contribution to the sustainability of agricultural production in greenhouses built on slope soils: A numerical study of the microclimatic behavior of a typical colombian structure. *Sustainability*, *13*(9), 4748. Online: https://doi.org/10.3390/su13094748

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., and David, C. (2009). Agroecology as a science, a movement and a practice. a review. *Agronomy for Sustainable Development*, *29*(4), 503–515. Online: https://doi.org/10.1051/agro/2009004