

AGRO PRODUCTIVIDAD

Scientific production trends on
***Macrobrachium
acanthurus***:
A bibliometric and network
analysis based on Scopus
pág. 255

Año 19 • Volumen 19 • Número 2 • febrero, 2026

Perception and attitude on water governance: design of indicators for Irrigation Districts in Mexico	3
Bovine respiratory disease and its effects on productive performance indicators and carcass yield	15
Evaluation of factors affecting milk production and composition in dual-purpose systems	25
Plant selection using a sequential decision algorithm based on an ideotype	37
Molecular detection of <i>Chlamydia</i> sp. in small ruminants from the central region of the state of Veracruz, Mexico	49
Productivity of maize genotypes in acid soils of southern Veracruz with and without dolomite	57

y más artículos de interés...




Colegio de
Postgraduados

CONTENIDO

Año 19 • Volumen 19 • Número 2 • febrero, 2026


3	Perception and attitude on water governance: design of indicators for Irrigation Districts in Mexico
15	Bovine respiratory disease and its effects on productive performance indicators and carcass yield
25	Evaluation of factors affecting milk production and composition in dual-purpose systems
37	Plant selection using a sequential decision algorithm based on an ideotype
49	Molecular detection of <i>Chlamydia</i> sp. in small ruminants from the central region of the state of Veracruz, Mexico
57	Productivity of maize genotypes in acid soils of southern Veracruz with and without dolomite
67	Earliness and productive efficiency in tropical black bean genotypes (<i>Phaseolus vulgaris</i> L.) under terminal drought
79	Efficacy of <i>Beauveria bassiana</i> as a biopesticide: A meta-analysis
89	Reduction in the incidence and recurrence of diarrhea in multibreed kids supplemented with <i>Bacillus subtilis</i> PB6 in Northern Mexico
97	Rooting of Tomato Cuttings in Nutrient Solution or Substrate: An Alternative for High-Density Production Systems
107	Introduction and use of Citlali and Ameyali potato varieties in family gardens in Zinacantepec, Mexico
115	Dragon fruit (<i>Hylocereus undatus</i>) crop yield: an analysis of innovations
123	Firmness and antioxidant compound changes in avocado (<i>Persea americana</i> Mill.) pulp during ripening at different storage temperatures
137	Economics of Animal Welfare: opportunities and challenges in an evolving market
151	Productive dynamics and sugarcane supply management in a competitive environment: a study of three sugar mills in Jalisco
163	Stakeholders and producers in the strawberry value chain: Perceptions and key challenges in Mexico's Bajío region
173	Profitability and comprehensive competitiveness of grain maize in a municipality in economic transition
183	GIS and modeling to determine key areas for conserving the genetic diversity of cotton (<i>Gossypium</i> spp.) in Mexico
195	Sustainable alternative: A forage prickly pear cactus (<i>Opuntia ficus-indica</i> L. Mill.) production system for cattle fattening
205	Ideal particle size in the main ingredients in pig feed
215	Altitudinal effect and multitemporal analysis of tree structure, distribution and richness in the Sierra Juárez of Ixtlán, Oaxaca, Mexico
233	Analysis of the Physicochemical Properties of "La Encantada" Lagoon During the Rainy Season in Lagunas de Montebello National Park, Chiapas
243	Response of piquín chili ecotypes (<i>Capsicum annuum</i> var. <i>aviculare</i> L.) to different shade coverage levels
255	Scientific production trends on <i>Macrobrachium acanthurus</i> : A Bibliometric and network analysis based on Scopus
267	Response of economic indicators of guava (<i>Psidium guajava</i> L.) production to public policies: Mexico


Comité Científico


Dr. Giuseppe Colla
University of Tuscia, Italia
 0000-0002-3399-3622


Dra. Magaly Sánchez de Chial
Universidad de Panamá, Panamá
 0000-0002-6393-9299

Dra. Maritza Escalona
Universidad de Ciego de Ávila, Cuba
 0000-0002-8755-6356

Dr. Kazuo Watanabe
Universidad de Tsukuba, Japón
 0000-0003-4350-0139

Dra. Ryoko Machida Hirano
Organización Nacional de Investigación en Agricultura y Alimentación (NARO-Japón)
 0000-0002-7978-0235

Dr. Ignacio de los Ríos Carmenado
Universidad Politécnica de Madrid, España
 0000-0003-2015-8983

Dra. María de Lourdes Arévalo Galarza
Colegio de Postgraduados, México
 0000-0003-1474-2300

Comité Editorial

Dr. Jorge Cadena Iñiguez - Editor en Jefe
Dra. Luccro del Mar Ruiz Posadas - Directora adjunta
Dr. Rafael Rodríguez Montessoro[†] - Director Fundador
Lic. BLS. Moisés Quintana Arévalo - Cosechador de metadatos
M.A. Ana Luisa Mejía Sandoval - Asistente
Téc. Mario Alejandro Rojas Sánchez - Diseñador
M.C. Valeria Abigail Martínez Sias - Diagramador



AGRICULTURA
SECRETARÍA DE AGRICULTURA Y DESARROLLO RURAL

AGRO PRODUCTIVIDAD



Colegio de Postgraduados

Bases de datos de contenido científico

ZOOLOGICAL RECORD[®]



Directorios



Año 19, Volumen 19, Número 2, febrero 2026, Agro productividad es una publicación mensual editada por el Colegio de Postgraduados. Carretera México-Texcoco Km. 36.5, Montecillo, Texcoco, Estado de México. CP 56264. Tel. 5959284427. www.colpos.mx. Editor responsable: Dr. Jorge Cadena Iñiguez. Reservas de Derechos al Uso Exclusivo No. 04-2017-031313492200-203. ISSN: 2594-0252, ambos otorgados por el Instituto Nacional del Derecho de Autor. Responsable de la última actualización de este número, M.C. Valeria Abigail Martínez Sias. Fecha de última modificación, 16 de abril de 2026.

Contacto principal
Jorge Cadena Iñiguez
Guerrero 9, esquina avenida Hidalgo,
C.P. 56220, San Luis Huexotla, Texcoco,
Estado de México.
✉ agroproductividadeditor@gmail.com

Contacto de soporte
Soporte
5959284703
✉ agroproductividadesoporte@gmail.com

Es responsabilidad del autor el uso de las ilustraciones, el material gráfico y el contenido creado para esta publicación.

Las opiniones expresadas en este documento son de exclusiva responsabilidad de los autores, y no reflejan necesariamente los puntos de vista del Colegio de Postgraduados, de la Editorial del Colegio de Postgraduados y del editor de la publicación.

Directrices para Autores/as


Naturaleza de los trabajos: Las contribuciones que se reciban para su eventual publicación deben ser resultados originales derivados de un trabajo académico de alto nivel sobre los tópicos presentados en la sección de temática y alcance de la revista.

Extensión y formato: Los artículos deberán estar escritos en procesador de textos, con una extensión de 15 cuartillas, tamaño carta con márgenes de 2.5 centímetros, Arial de 12 puntos, interlineado doble, sin espacio entre párrafos. Las páginas deberán estar foliadas desde la primera hasta la última en el margen inferior derecho. La extensión total incluye abordaje textual, bibliografía, gráficas, figuras, imágenes y todo material adicional. Debe evitarse el uso de sangría al inicio de los párrafos. Las secciones principales del artículo deberán escribirse en mayúsculas, negritas y alineadas a la izquierda. Los subtítulos de las secciones se escribirán con mayúsculas sólo la primera letra, negritas y alineadas a la izquierda.

Exclusividad: Los trabajos enviados a Agro Productividad deberán ser inéditos y sus autores se comprometen a no someterlos simultáneamente a la consideración de otras publicaciones; por lo que es necesario adjuntar este documento: Carta de originalidad.

Frecuencia de publicación: Cuando un autor ha publicado en la revista como autor principal o de correspondencia, deberá esperar tres números de ésta para publicar nuevamente como autor principal o de correspondencia.

Idiomas de publicación: Se recibirán textos en inglés con títulos, resúmenes y palabras clave en inglés.

ID Autores: El nombre de los autores se escribirán comenzando con el apellido o apellidos unidos por guion, sólo las iniciales del nombre, separados por comas, con un índice progresivo en su caso. Es indispensable que todos y cada uno de los autores proporcionen su número de identificador normalizado  ORCID, para mayor información ingresar a (<https://orcid.org>).

Institución de adscripción: Es indispensable señalar la institución de adscripción y país de todos y cada uno de los autores, indicando exclusivamente la institución de primer nivel, sin recurrir al uso de siglas o acrónimos. Se sugiere recurrir al uso de la herramienta wayta (<http://wayta.scielo.org/>) de Scielo para evitar el uso incorrecto de nombres de instituciones.

Anonimato en la identidad de los autores: Los artículos no deberán incluir en ni en cuerpo del artículo, ni en las notas a pie de página ninguna información que revele su identidad, esto con el fin de asegurar una evaluación anónima por parte de los pares académicos que realizarán el dictamen. Si es preciso, dicha información podrá agregarse una vez que se acredite el proceso de revisión por pares.

Estructura de los artículos: Los artículos incluirán los siguientes elementos: Título, title, autores y adscripción, abstract, keywords, resumen, palabras clave, introducción, objetivos, materiales y métodos, resultados y discusión, conclusiones y literatura citada en formato APA.

Título: Debe ser breve y reflejar claramente el contenido, deberá estar escrito en español e inglés. Cuando se incluyan nombres científicos deben escribirse en *italicas*. No deberá contener abreviaturas ni exceder de 20 palabras, se usará solo letras mayúsculas, en **negritas**, centrado y no llevará punto final.

Resumen y Abstract: Deberá integrarse un resumen en inglés y español (siguiendo ese orden), de máximo 250 palabras, donde se destaque obligatoriamente y en este orden: a) objetivo; b) diseño / metodología / aproximación; c) resultados; d) limitaciones / implicaciones; e) hallazgos/ conclusiones. El resumen no deberá incluir citas, referencias bibliográficas, gráficas ni figuras.

Palabras clave y Keywords: Se deberá incluir una lista de 3 a 5 palabras clave en español e inglés que permitan identificar el ámbito temático que aborda el artículo.

Introducción: Se asentará con claridad el estado actual del conocimiento sobre el tema investigado, su justificación e importancia, así como los objetivos del trabajo. No deberá ser mayor a dos cuartillas.

Materiales y Métodos: Se especificará cómo se llevó a cabo la investigación, incluyendo el tipo de investigación, diseño experimental (cuando se traten de investigaciones experimentales), equipos, sustancias y materiales empleados, métodos, técnicas, procedimientos, así como el análisis estadístico de los datos obtenidos.

Resultados y Discusión: Puede presentarse en una sola sección. En caso de presentarse de forma separada, la discusión debe enfocarse a comentar los resultados (sin repetirlos), en términos de sus características mismas, su congruencia con la hipótesis planteada y sus semejanzas o diferencias con resultados de investigaciones similares previamente realizadas.

Conclusiones: Son la generalización de los resultados obtenidos; deben ser puntuales, claras y concisas, y no deben llevar discusión, haciendo hincapié en los aspectos nuevos e importantes de los resultados obtenidos y que establezcan los parámetros finales de lo observado en el estudio.

Agradecimientos: Son opcionales y tendrán un máximo de tres renglones para expresar agradecimientos a personas e instituciones que hayan contribuido a la realización del trabajo.

Cuadros: Deben ser claros, simples y concisos. Se ubicarán inmediatamente después del primer párrafo en el que se mencionen o al inicio de la siguiente cuartilla. Los cuadros deben numerarse progresivamente, indicando después de la referencia numérica el título del mismo (Cuadro 1. Título), y se colocarán en la parte superior. Al pie del cuadro se incluirán las aclaraciones a las que se hace mención mediante un índice en el texto incluido en el cuadro. Se recomienda que los cuadros y ecuaciones se preparen con el editor de tablas y ecuaciones del procesador de textos.

Uso de siglas y acrónimos: Para el uso de acrónimos y siglas en el texto, la primera vez que se mencionen, se recomienda escribir el nombre completo al que corresponde y enseguida colocar la sigla entre paréntesis. Ejemplo: Petróleos Mexicanos (Pemex), después sólo Pemex.

Elementos gráficos: Corresponden a dibujos, gráficas, diagramas y fotografías. Deben ser claros, simples y concisos. Se ubicarán inmediatamente después del primer párrafo en el que se mencionen o al inicio de la siguiente cuartilla. Las figuras deben

numerarse progresivamente, indicando después de la referencia numérica el título del mismo (Figura 1. Título), y se colocarán en la parte inferior. Las fotografías deben ser de preferencia a colores y con una resolución de 300 dpi en formato JPG, TIF o RAW. El autor deberá enviar 2 fotografías adicionales para ilustrar la página inicial de su contribución. Las gráficas o diagramas serán en formato de vectores (CDR, EPS, AI, WMF o XLS).

Unidades. Las unidades de pesos y medidas usadas serán las aceptadas en el Sistema Internacional.

Citas bibliográficas: deberán insertarse en el texto abriendo un paréntesis con el apellido del autor, el año de la publicación y la página, todo separado por comas. Ejemplo (Zheng *et al.*, 2017). El autor puede introducir dos distintos tipos de citas:

Citas directas de menos de 40 palabras: Cuando se transcriben textualmente menos de 40 palabras, la cita se coloca entre comillas y al final se añade entre paréntesis el autor, el año y la página. Ejemplo:

Alineado al Plan Nacional de Desarrollo 2013-2018, (DOF, 2013), el Programa Sectorial de Desarrollo Agropecuario, Pesquero y Alimentario 2013-2018 establece “Construir un nuevo rostro del campo sustentado en un sector agroalimentario productivo, competitivo, rentable, sustentable y justo que garantice la seguridad alimentaria del país” (DOF, 2013).

Citas indirectas o paráfrasis: Cuando se interpretan o se comentan ideas que son tomadas de otro texto, o bien cuando se expresa el mismo contenido pero con diferente estructura sintáctica. En este caso se debe indicar el apellido del autor y el año de la referencia de donde se toman las ideas. Ejemplo:

Los bajos rendimientos del cacao en México, de acuerdo con Avendaño *et al.* (2011) y Hernández-Gómez *et al.* (2015); se debe principalmente a la edad avanzada de las plantaciones.

Las referencias bibliográficas: al final del artículo deberán indicarse todas y cada una de las fuentes citadas en el cuerpo del texto (incluyendo notas, fuentes de los cuadros, gráficas, mapas, tablas, figuras etcétera). El autor(es) debe revisar cuidadosamente que no haya omisiones ni inconsistencias entre las obras citadas y la bibliografía. Se incluirá en la lista de referencias sólo las obras citadas en el cuerpo y notas del artículo. La bibliografía deberá presentarse estandarizada recurriendo a la norma APA, ordenarse alfabéticamente según los apellidos del autor.

De haber dos obras o más del mismo autor, éstas se listan de manera cronológica iniciando con la más antigua. Obras de un mismo autor y año de publicación se les agregará a, b, c... Por ejemplo:

Ogata N. (2003a).
Ogata N. (2003b).

Artículo de revista:

Wang, P., Zhang, Y., Zhao, L., Mo, B., & Luo, T. (2017). Effect of Gamma Rays on *Sophora davidii* and Detection of DNA Polymorphism through ISSR Marker [Research article]. <https://doi.org/10.1155/2017/8576404>

Libro:

Turner J. (1972). Freedom to build, dweller control of the housing process. New York: Macmillan.

Uso de gestores bibliográficos: Se dará prioridad a los artículos enviados con la bibliografía gestionada electrónicamente, y presentada con la norma APA. Los autores podrán recurrir al uso de cualquier gestor disponible en el mercado (Reference Manager, Crossover o Mendeley entre otros), o de código abierto tal como Refworks o Zotero.

Perception and attitude on water governance: design of indicators for Irrigation Districts in Mexico

Cuéllar-Lugo, Martha B.¹; Asiain-Hoyos, Alberto^{1*}; Díaz-Rivera, Pablo¹; Suárez-Sánchez, Juan²; Hernández-Pérez, Juan M.¹; Alvarez-Avila, María del C.¹; Partida-Sedas, Salvador¹; Gallardo-López, Felipe¹

¹ Colegio de Postgraduados Campus Veracruz. km 88.5 Carretera Federal Xalapa-Veracruz, vía Paso de Ovejas, entre Puente Jula y Paso San Juan, Tepetates, Manlio F. Altamirano, Veracruz. C.P. 91669.

² Universidad Autónoma de Tlaxcala. Av. Universidad No. 1, La Loma Xico-tencatl. Tlaxcala, Tlaxcala. C.P. 90070.

* Correspondence: aasiain@colpos.mx

ABSTRACT

Objective: to define the selection criteria for the design and validation of a methodological tool that operationalizes the water governance concept across the perception and attitude of stakeholders for efficient water management in Irrigation Districts.

Design/methodology/approach: a questionnaire was designed and validated to assess perception and attitude variables in water governance, structuring the methodology in four phases. Initially, a contextualized conceptual framework was constructed to define a system of indicators with theoretical rigour. Subsequently, the psychometric operationalization of the variables into measurable items was carried out. A priori validation was performed using the Delphi technique, with a multidisciplinary panel of experts. Finally, a posteriori validation will empirically contrast the results to consolidate a robust diagnostic tool for longitudinal application.

Limitations/implications: the subjective nature of the constructs measured (perception and attitude), whose validity may be compromised in relation to observable behaviors. Nevertheless, the instrument is a reliable methodological tool for the empirical diagnosis and longitudinal monitoring of water governance.

Findings/conclusions: a methodological tool was developed that operationalizes intangible constructs of perception and attitude into quantifiable indicators for water governance. Validated using the Delphi method, it allows critical indicators such as institutional trust and perceived equity to be measured. This tool is a strategic resource for longitudinal diagnoses and the design of interventions towards more transparent and efficient water management.

Keywords: water management, methodological framework, irrigation water, community participation, socio-ecological systems.

Citation: Cuéllar-Lugo, M. B., Asiain-Hoyos, A., Díaz-Rivera, P., Suárez-Sánchez, J., Hernández-Pérez, J. M., Álvarez-Ávila, M. del C., Partida-Sedas, S., & Gallardo-López, F. (2026). Perception and attitude on water governance: design of indicators for Irrigation Districts in Mexico. *Agro Productividad*. <https://doi.org/10.32854/fwswhe62>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: November 14, 2025.

Accepted: January 18, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 3-13.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Water governance (WG) is considered an integral and complex approach, which is made up of political, economic, social and environmental systems (Linh *et al.*, 2025;



Rosso, 2025). Within this framework, government actors, civil society, and the private sector interact (Bocarejo *et al.*, 2018; Victoria, 2018), whose work encompasses the development, management, and efficient handling of water resources (Garate *et al.*, 2023). Its effectiveness depends on the co-production that arises from the combination of participatory and inclusive processes, which incorporate local knowledge, accompanied by specialized technical knowledge (Klingaman *et al.*, 2024; Ngonyani *et al.*, 2024). This synergy is fundamental to strengthening resilience and adaptation to water scarcity (Aroy *et al.*, 2025; Datta *et al.*, 2025; Sahani *et al.*, 2025).

This is how GA has become a central paradigm that promotes: active and inclusive participation, adaptation to changing contexts, the incorporation of principles of distributive, procedural and recognition justice, as well as the search for solutions that respond to local realities (Lukas *et al.*, 2024; Linh *et al.*, 2025).

Irrigation Districts (IDs) represent a specific context for the application of this paradigm. According to Suárez and Obregón (2024), these constitute a complex socio-ecological system, embedded in a territory equipped with hydraulic infrastructure, which facilitates the distribution and management of water to support socioeconomic and agricultural growth. To improve their performance, effective participation of farmers, communities, authorities, and other key stakeholders is required for shared decision-making and joint conflict resolution (Altamirano *et al.*, 2019; Castañeda, 2021; Jariego, 2024; Lukas *et al.*, 2024). However, the effectiveness of these participatory processes is determined by subjective dimensions of the actors, where perception and attitude are fundamental factors.

Perception, understood as the cognitive process by which the brain organizes, interprets, and gives meaning to environmental stimulus (Fréré Arauz *et al.*, 2022), is influenced by prior experiences, emotions, and cultural context. This process significantly conditions the acceptance of policies and the adoption of sustainable practices (López-Porras *et al.*, 2018; Rosas-Baños *et al.*, 2023). Similarly, attitude, defined as a psychological tendency composed of cognitive, affective, and behavioral components that influences the evaluation of specific entities, exerts a direct influence on water management (Fishman *et al.*, 2021). Thus, while attitudinal differences can hinder distribution and generate inequalities (Velasco-Muñoz *et al.*, 2023), there are also favorable positions towards conservation.

Taken together, the perception of equity, transparency, and institutional trust, along with attitudes toward cooperation, are crucial for the self-organization and sustainability of irrigation systems (Howell *et al.*, 2023; Whitley, 2024).

In this context, the operationalization of perception and attitude constitutes a fundamental methodological tool. Capturing these subjective dimensions of water governance allows for the identification of patterns associated with greater technical efficiency, environmental sustainability, conflict reduction, and improved self-organization in irrigation systems. Therefore, this research aimed to define the selection criteria for the design and validation of a methodological tool that operationalizes the concept of water governance through the variables of users' perception and attitude for efficient water management in the IDs.

MATERIALS AND METHODS

This research employed a four-phase methodological design for the development and validation of an instrument (Figure 1) used to assess perception and attitude variables in water governance. This process adhered to rigorous conceptual standards, analyzing scientific sources to ensure the tool’s validity, reliability, and practical utility (Sinharoy *et al.*, 2022).

Phase 1. Conceptual design. A reference framework was constructed, integrated into the context of the IDs, based on methodologies such as: the Organization for Economic Cooperation and Development (OECD, 2018), the United Nations Development Programme (UNDP, 2015) and the Mexican Institute of Water Technology (IMTA, 2023); to define the dimensions of the indicator system (Pires *et al.*, 2017; Benson *et al.*,

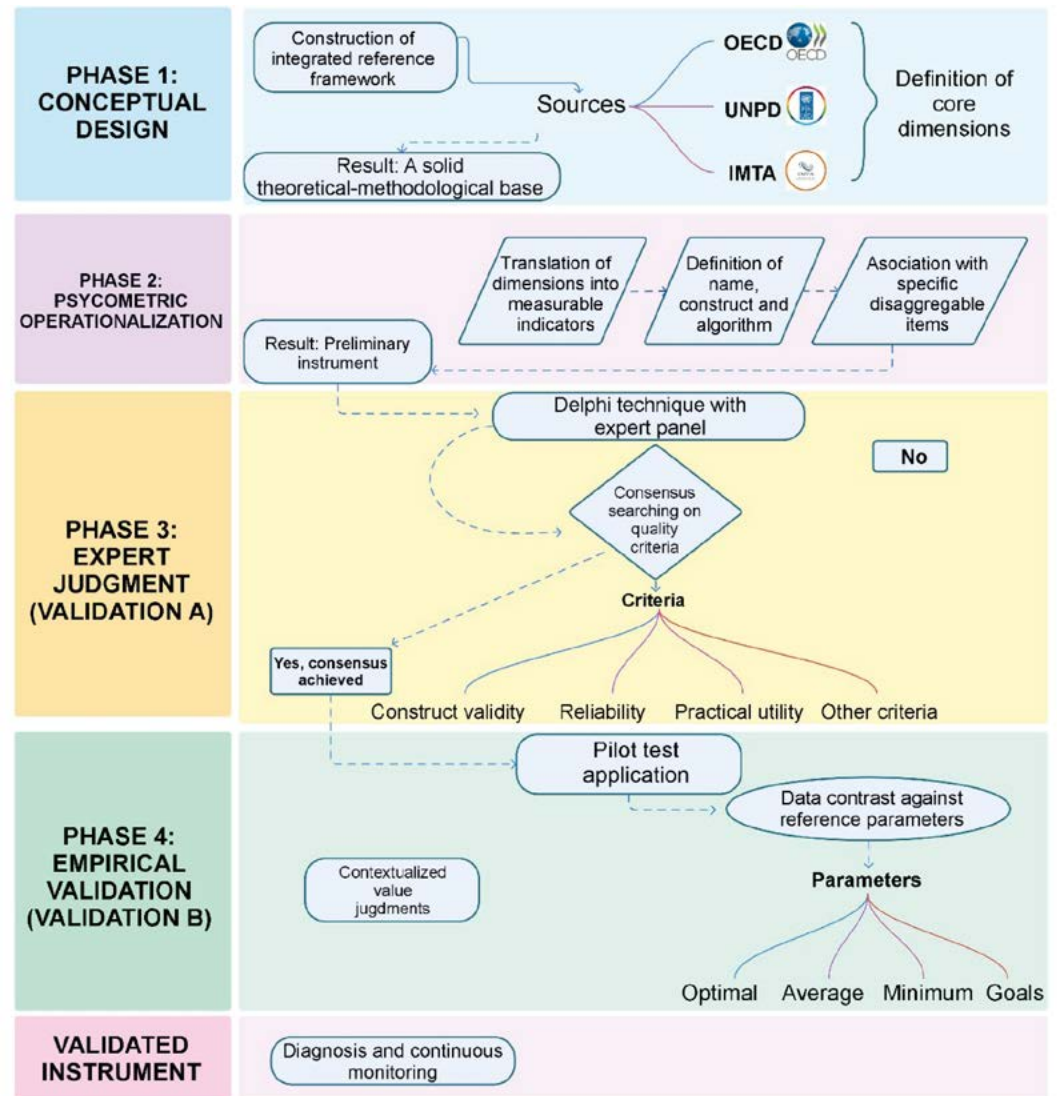


Figure 1. Methodological design for the evaluation of the perception and attitude of water governance in Irrigation Districts (IDs) in Mexico. Source: Own elaboration.

2019; Costa & Neto, 2023). This theoretical and methodological basis prevents the mere grouping of indicators without a logical and systemic structure (Schneider *et al.*, 2015; Linh *et al.*, 2025).

Phase 2. Psychometric Operationalization. The operationalization of each conceptual dimension allowed the construction of measurable indicators associated with the perception and attitude variables, using specific items adapted to different key stakeholders (Kang, 2022; Nelson *et al.*, 2024), such as producers, technicians, and authorities. In this phase, the names of the indicators, their theoretical meaning, and the calculation method were defined (Azevêdo *et al.*, 2022).

Phase 3. Expert Judgment Validation (*a priori*). For this phase, it was proposed to use the Delphi technique to form a multidisciplinary panel of experts and key users, thus ensuring diversity and experience in the instrument's domain (Mariano *et al.*, 2022; Alaze *et al.*, 2025). Subsequently, it undergoes constant rounds of anonymous evaluation, where experts assess each item according to the defined criteria and suggest improvements (Dragostinov *et al.*, 2022; Lim & Park, 2025) for application in a pilot test.

Phase 4. Empirical validation and comparison (*a posteriori*). The instrument was validated by comparing the results with reference parameters to evaluate the actors' performance (Dima, 2018). The results obtained served as a guide for making contextualized judgments, adapting the assessment to specific realities and goals (Renaud *et al.*, 2020), on the complex constructs of water governance in irrigation districts in Mexico. This process establishes that the tool is consolidated as a reliable system for the diagnosis and longitudinal monitoring of water management, allowing for adjustments and continuous improvements based on the results obtained (Gibbons *et al.*, 2021).

RESULTS AND DISCUSSION

Contextual analysis of the methodological framework

Currently, in the Mexican context, there is an increase in institutional distrust, in participation in decision-making, and in the adoption of efficient practices in the use and management of water due to centralized bureaucratic management and the perception of a deficient institutional system that harms agricultural producers (Hunecke *et al.*, 2017; Navarro-Frómeta *et al.*, 2019). Thus, overcoming these challenges requires interventions that prioritize and restore social trust through concrete positive experiences and the genuine strengthening of user associations and the effective decentralization of decision-making (Aquino-López and Aguilar-Sánchez, 2019), which can create a change towards effective governance.

Governance, particularly water governance, is recognized as a fundamental, multidimensional construct for sustainable water management (Duc *et al.*, 2024; Mishra *et al.*, 2021), primarily in scenarios where guaranteeing the human right to water faces substantial social and institutional challenges. Bilalova *et al.* (2024) mentioned that this approach encompasses political, social, economic, environmental, ethical and legal dimensions, and is essential to address the complexity and conflicts inherent in the management of this resource (Jiménez *et al.*, 2020).

Methodologies such as the one designed by the Organisation for Economic Co-operation and Development (OECD, 2018) provide a conceptual framework based on rules, practices, and multi-level processes. These methodologies analyze water governance through the following dimensions: effectiveness, which refers to the capacity of governance to define clear and sustainable water policy goals and objectives at different levels of government, implement these objectives, and achieve the expected results; efficiency, which relates to the contribution of governance to maximizing the benefits of sustainable water management and social welfare at the lowest possible cost; and trust and participation, which relates to the capacity of governance to build trust among the population and ensure the inclusion of stakeholders through democratic legitimacy and equity for society in general (Villa-Landa & Perero Van Hove, 2022).

Similarly, the methodology developed by the United Nations Development Programme (UNDP, 2015) is based on the following dimensions: social, which seeks the equitable use of water resources; environmental, fostering the sustainable use of the resource and the conservation of ecosystems; and political, aimed at social empowerment, so that stakeholders and citizens have equal opportunities to influence and monitor political processes and water management (Abbas *et al.*, 2023). This achieves equity, efficiency, sustainability, and the effective participation of all actors, especially vulnerable groups, in decision-making and oversight of water management, thus making the human right to water a reality.

Finally, in the Mexican context, the Mexican Institute of Water Technology (IMTA, 2023) has a methodology that has resulted in the design of indicators aligned with state obligations, organized into analytical categories such as normative reception of the right, budgetary commitment, institutional capacities, substantive equality, access to information, and justice mechanisms. Regarding these proposed methodological frameworks, Norberto-Cárdenas *et al.* (2024) stated that the indicators reflect a broader effort to strengthen institutional transparency and legal frameworks in water management, suggesting a comprehensive and structured approach to water rights and governance.

The integration of these three frameworks demonstrates that, beyond the differences in their methodological structures, they share a common concept: effective governance. This requires institutional strength, inclusive and genuine citizen participation, and well-defined accountability mechanisms. Furthermore, applying these methodological frameworks to the reality of irrigation districts in Mexico reveals challenges that transcend the technical and are deeply rooted in the social subconscious. Therefore, Bautista-Capetillo *et al.* (2025) stated that a comprehensive approach is needed that combines technical improvements with public policies, financial support, and strengthened collaborative networks to achieve the effective and sustainable adoption of technologies in irrigation districts.

Operationalization of variables

Conceptual analysis of perception and attitude to design indicators on water governance

The psychometric operationalization of variables constitutes a fundamental methodological advance for understanding and translating subjective dimensions into

quantitative data, which strengthen the management and evaluation of governance (Müller & Lecoeuvre, 2014; Mubiri *et al.*, 2024). Based on this analysis, and through the triangulation of methodological frameworks such as those proposed by the OECD, UNDP, and IMTA, the concepts of perception and attitude were operationalized into variables, enabling the development of a series of indicators, ranging from institutional trust to willingness to adopt innovations. The aim was to focus on the behavior, willingness, and stance of users to adopt technological proposals for efficient management in irrigation districts (Abila *et al.*, 2024; Adla *et al.*, 2024). This dual construction, perception-attitude, is a methodological contribution that allows us to interpret reality and behavioral predispositions (Castillo *et al.*, 2021), to offer a more holistic understanding of the factors that influence the effectiveness of water governance at the local level (Table 1).

Validation through the expert panel

Based on the operationalization, the indicators to be validated were selected using the Delphi technique, which aims to form a judgment based on the opinions of a group of experts (Niederberger & Spranger, 2020). For the application of this method, anonymous participation must be considered in an iterative process of at least two rounds, where the experts are given feedback on the results obtained (Drumm *et al.*, 2022). In addition, this technique requires the selection of experts, through criteria such as qualitative aspects, such as the k coefficient of expert competence (Cabero-Almenara *et al.*, 2020; Fernández-Gómez *et al.*, 2020).

In this research, the dimensions of the first version of the questionnaire were defined: 1) the respondent's experience in the efficient use and management of water; 2) knowledge of the administrative and technical operation of irrigation districts; and 3) analysis of the perception and behavioral attitudes of small-scale producer groups. Based on these characteristics, 10 experts were invited to evaluate the relevance, clarity, wording, and consistency of the response options for the items, using a dichotomous scale of “yes” and “no” (Curteanu *et al.*, 2025).

Aiken's V will be calculated to measure the content validity of a measurement instrument and identify the relevance of the items with respect to the specific domain of the group of experts (Barbosa & Cansino, 2022; Sierra-Barón *et al.*, 2025).

The calibration and validation carried out through this rigorous methodological process has resulted in a scientifically sound, culturally adapted questionnaire capable of generating reliable data to diagnose and improve water management in the Irrigation Districts of Mexico.

CONCLUSIONS

The development and validation of the questionnaire presented in this research constitutes a substantial methodological contribution to the field of water governance. Its main innovation lies in the systematic operationalization of intangible constructs—that is, the perceptions and attitudes of IDs users—through a system of quantifiable indicators, supported by conceptual frameworks from international organizations and validated using

Table 1. Construction of indicators on the perception and attitude on water governance in Irrigation Districts in Mexico.

CONSTRUCT 1: USERS' PERCEPTION OF WATER GOVERNANCE IN THE IDs	
Dimension Conceptual	Perception Indicator
Legal Framework	Level of knowledge of the internal regulations of the IDs
	Perception of the clarity of the requirements for accessing water
Equity	Perception of the frequency of preferential treatment in water allocation
	Perception of impartiality in conflict resolution
Coordination	Perception of the quality of the relationship between users and their representatives
	Perception of the fulfillment of duties by the IDs
Stake	Perception of opportunities to participate in IDs decisions
	Perception of the attention given to needs by the IDs
Administration : Personnel	Perception of the quality of care provided by IDs staff
	Perception of staff training in water management
Administration : Finance	Perception of transparency in the use of resources
	Perception of fairness in the calculation of quotas
Sustainability	Perception of the volume of water available for irrigation
	Perception of the degree of water waste in the system
	Perception of the adoption of water efficiency technologies
CONSTRUCT 2: USERS' ATTITUDE TOWARDS WATER GOVERNANCE IN THE IDs	
Dimension Conceptual	Attitude Indicator
Legal Framework	Assessment of the need to update the internal regulations
	Level of agreement with the rigor in the application of the regulations
Equity	Level of confidence in the impartiality of IDs staff
	Assessment of mechanisms to prevent discrimination
Coordination	Willingness to collaborate in IDs improvement activities
	Assessment of communication with the IDs
Stake	Appreciation of the importance of participating in decisions
	Willingness to attend regular assemblies
Administration : Personnel	Assessment of the need to train staff
	Level of satisfaction with the service received
Administration : Finance	Level of agreement with increased fees for better service
	Assessment of the need for external audits
Sustainability	Willingness to implement sustainable practices
	Concern about the effects of climate change
	Assessing the importance of infrastructure maintenance

Source: Own elaboration.

the Delphi method. This methodological rigor moves beyond purely descriptive approaches, facilitating the measurement of critical indicators such as institutional trust, perceived equity in water distribution, and the predisposition to adopt technologies. The tool thus provides a reliable empirical basis for conducting longitudinal assessments, identifying critical points in management, and designing specific interventions. Consequently, it stands as a strategic resource for transitioning toward adaptive governance in the IDs, promoting more transparent, inclusive, and technically informed management.

ACKNOWLEDGMENTS

The lead author thanks SECIHTI for the funding of her doctoral studies, which enabled her to develop her research project at the Colegio de Postgraduados, Campus Veracruz. She also extends her gratitude to the Scientific Committee of the 37th Scientific-Technological, Forestry and Agricultural Meeting Veracruz 2025 for selecting this work for publication.

REFERENCES

- Abbas, F., Al-Naemi, S., Farooque, A. A., & Phillips, M. (2023). A Review on the Water Dimensions, Security, and Governance for Two Distinct Regions. *Water*, *15*(1), 208. <https://doi.org/10.3390/w15010208>
- Abila, D., D., Asokhan, M., Balasubramaniam, P., & Kumaresan, P. (2024). Perception and adoption of drip irrigation technology among beneficiaries of the Tamil Nadu Irrigated Agriculture Modernization Project: A Structural Equation Modelling approach. *Plant Science Today*, *11*(sp4), 1-9. <https://doi.org/10.14719/pst.5795>
- Adla, S., Šaponjić, A., Tyagi, A., Nagi, A., Pastore, P., & Pande, S. (2024). Steering agricultural interventions towards sustained irrigation adoption by farmers: socio-psychological analysis of irrigation practices in Maharashtra, India. *Hydrological Sciences Journal*, *69*(12), 1586-1603. <https://doi.org/10.1080/02626667.2024.2376709>
- Alaze, A., Finne, E., Razum, O., & Miani, C. (2025). A questionnaire for a conceptual framework and interdisciplinary public health research using the Delphi technique-development and validation. *Frontiers in Public Health*, *13*, 1436569. <https://doi.org/10.3389/fpubh.2025.1436569>
- Altamirano, A., A., Valdez, T., J. B., Valdez, L., C., León, B., J. I., Betancourt, L., M., & Osuna, E., T. (2019). Evaluación del desempeño de los distritos de riego en México mediante análisis de eficiencia técnica / Performance assessment of irrigation districts in Mexico through technical efficiency analysis. *Tecnología y Ciencias del Agua*, *10*(1), 85-121. <https://doi.org/10.24850/j-tyca-2019-01-04>
- Aquino-López, V. D., & Aguilar-Sánchez, G. (2019). Environmental governability in the water use of irrigation district 023-San Juan del Río, Querétaro. *Agricultura, Sociedad y Desarrollo*, *16*(3), 331-349. <https://doi.org/10.22231/asyd.v16i3.1233>
- Aroy, P., C., Torrentira, Jr., M. C., & Joel, U., L. (2025). Developing Sustainable Water Supply Strategies among Indigenous Peoples in the Davao Region: A Systematic Review. *International Journal of Social Science and Education Research Studies*, *5*(1), 01-07. <https://doi.org/10.55677/ijssers/v05i01y2025-01>
- Azevêdo, E. L., Alves, R. R. N., Dias, T. L. P., Álvaro, É. L. F., Barbosa, J. E. L., & Molozzi, J. (2022). Perception of the local community: What is their relationship with environmental quality indicators of reservoirs? *PLOS ONE*, *17*(1), e0261945. <https://doi.org/10.1371/journal.pone.0261945>
- Barbosa, M., & Cansino, J. (2022). A Water Footprint Management Construct in Agri-Food Supply Chains: A Content Validity Analysis. *Sustainability*, *14*(9), 4928. <https://doi.org/10.3390/su14094928>
- Bautista-Capetillo, C., Pineda-Martínez, H., Flores-Chaires, L., & Pineda-Martínez, L. (2025). Agriculture Resilient at Three Irrigation Modules of Zacatecas, Mexico: Water Scarcity and Climate Variability. *Agronomy*, *15*(4), 800. <https://doi.org/10.3390/agronomy15040800>
- Benson, D., Gain, A., & Giupponi, C. (2019). Moving beyond water centrality? Conceptualizing integrated water resources management for implementing sustainable development goals. *Sustainability Science*, *15*, 671-681. <https://doi.org/10.1007/s11625-019-00733-5>
- Bilalova, S., Newig, J., & Villamayor-Tomas, S. (2025). Toward Sustainable Water Governance? Taking Stock of Paradigms, Practices, and Sustainability Outcomes. *WIREs Water*, *12*(1), e1762. <https://doi.org/10.1002/wat2.1762>

- Bocarejo, S., D. (2018). Gobernanza del agua: pensar desde las fluctuaciones, los enmarañamientos y políticas del día a día. *Revista de Estudios Sociales*, 1(63), 111-118. <https://doi.org/10.7440/res63.2018.09>
- Cabero-Almenara, J., Romero-Tena, R., & Palacios-Rodríguez, A. (2020). Evaluation of teacher digital competence frameworks through expert judgement: The use of the expert competence coefficient. *Journal of New Approaches in Educational Research (NAER Journal)*, 9(2), 275-293. <https://www.learntechlib.org/P/217617/>
- Castañeda, V., A. A. (2021). Evolución de la gestión del agua en municipios de México: Estudio de un Organismo Público Descentralizado en Los Altos de Jalisco (2013-2018). *Agua y Territorio, Water and Landscape*, 17, 33-54. <https://doi.org/10.17561/at.17.5518>
- Costa, M. M., & Neto, S. (2023). Exploratory analysis of the water governance frameworks regarding the OECD principles in two river basins in Brazil and Portugal. *Utilities Policy*, 82. <https://doi.org/10.1016/j.jup.2023.101556>
- Curteanu, M., Marinescu, V., Ferdohleb, A., Bahnarel, I., Pinzaru, I., & Ciobanu, E. (2025). Testing and validation of the questionnaire for evaluating the chemical composition of bottled water in relation to public health. *Moldovan Journal of Health Sciences*, 1(12), 41-47. <https://doi.org/10.52645/mjhs.2025.1.07>
- Datta, R., Chapola, J., & Lewis, K. (2025). Rethinking Indigenous Community-Led Water Sustainability: Decolonial and Relational Approaches in Western Canada. *Water*, 17(3), 334. <https://doi.org/10.3390/w17030334>
- Dima, A. (2018). Scale validation in applied health research: tutorial for a 6-step R-based psychometrics protocol. *Health Psychology and Behavioral Medicine*, 6(1), 136-161. <https://doi.org/10.1080/21642850.2018.1472602>
- Dragostinov, Y., Harðardóttir, D., McKenna, P., Robb, D., Nessel, B., Ahmad, M., Romeo, M., Lim, M., Yu, C., Jang, Y., Diab, M., Cangelosi, A., Demiris, Y., Hastie, H., & Rajendran, G. (2022). Preliminary psychometric scale development using the mixed methods Delphi technique. *Methods in Psychology*, 7, 100103. <https://doi.org/10.1016/j.metip.2022.100103>
- Drumm, S., Bradley, C., & Moriarty, F. (2022). 'More of an art than a science'? The development, design and mechanics of the Delphi Technique. *Research in Social and Administrative Pharmacy*, 18(1), 2230-2236. <https://doi.org/10.1016/j.sapharm.2021.06.027>
- Duc, N. H., Kumar, P., Long, P. T., Meraj, G., Lan, P., Almazroui, M., & Avtar, R. (2024). A Systematic Review of Water Governance in Asian Countries: Challenges, Frameworks, and Pathways Toward Sustainable Development Goals. *Earth Systems and Environment*, 8, 181-205. <https://doi.org/10.1007/s41748-024-00385-1>
- Fernández-Gómez, E., Martín-Salvador, A., Luque-Vara, T., Sánchez-Ojeda, M. A., Navarro-Prado, S., & Enrique-Mirón, C. (2020). Content validation through expert judgement of an instrument on the nutritional knowledge, beliefs, and habits of pregnant women. *Nutrients*, 12(4), 1136. <https://doi.org/10.3390/nu12041136>
- Fishman, J., Yang, C., & Mandell, D. (2021). Attitude theory and measurement in implementation science: a secondary review of empirical studies and opportunities for advancement. *Implementation Science: IS*, 16. <https://doi.org/10.1186/s13012-021-01153-9>
- Gárate, R., J., Pashanasi, A., B., Palomino, A., G. del P., & Pereyra, G., T. V. (2023). Gobernanza del agua: un análisis sistemático de desafíos, temáticas y propuestas para una gestión hídrica sostenible. *Producción + Limpia*, 18(2), 116-138. <https://doi.org/10.22507/pml.v18n2a7>
- Gibbons, C., Porter, I., Gonçalves-Bradley, D., Stoilov, S., Ricci-Cabello, I., Tsangaris, E., Gangannagaripalli, J., Davey, A., Gibbons, E., Kotzeva, A., Evans, J., Van Der Wees, P., Kontopantelis, E., Greenhalgh, J., Bower, P., Alonso, J., & Valderas, J. (2021). Routine provision of feedback from patient-reported outcome measurements to healthcare providers and patients in clinical practice. *The Cochrane database of systematic reviews*, 10, CD011589. <https://doi.org/10.1002/14651858.cd011589.pub2>
- Howell, C. L., Cortado, A. P., & Ünver, O. (2023). Stakeholder Engagement and Perceptions on Water Governance and Water Management in Azerbaijan. *Water*, 15(12), 2201. <https://doi.org/10.3390/w15122201>
- Hunecke, C., Engler, A., Jara Rojas, R., & Poortvliet, P. (2017). Understanding the role of social capital in adoption decisions: An application to irrigation technology. *Agricultural Systems*, 153, 221-231. <https://doi.org/10.1016/j.agsy.2017.02.002>
- IMTA [Instituto Mexicano de Tecnología del Agua]. (2023). Indicadores de Derechos Humanos al Agua y al Saneamiento en México 2023. Escobar, N. C y Zavala, V. L. C. (Eds). IMTA. Jiutepec. Morelos. 200p. <https://www.imta.gob.mx/gobmx/DOI/libros/2023/Libro-indicadores-derechos-humanos-agua-saneamiento.pdf>

- Jiménez, A., Saikia, P., Giné, R., Avello, P., Leten, J., Liss Lymer, B., Schneider, K., & Ward, R. (2020). Unpacking Water Governance: A Framework for Practitioners. *Water*, 12(3), 827. <https://doi.org/10.3390/w12030827>
- Kang, T. (2022). Construction and Empirical Analysis of Citizens' Water Literacy Evaluation Index System: A Structural Equation Model. *Water Resour Manage*, 36, 1393-1411. <https://doi.org/10.1007/s11269-022-03089-1>
- Klingaman, E., Baghirzade, B., Rowles, L., Toledo-Flores, L., Pérez-Flores, M., López-Cruz, J., & Saleh, N. (2024). Strengths of Zapotec Indigenous Knowledge in Water Management. *ACS ES&T Water*, 4(6), 2382-2389. <https://doi.org/10.1021/acsestwater.3c00731>
- Lanza, C., G. M., Engler, A., & Wollni, M. (2021). Planned behavior and social capital: Understanding farmers' behavior toward pressurized irrigation technologies. *Agricultural Water Management*, 243, 106524. <https://doi.org/10.1016/j.agwat.2020.106524>
- Lim, S., & Park, J. H. (2025). Development of a questionnaire for problematic social networking sites use: Ensuring content validity through Delphi methodology. *PLOS ONE*, 20(3), e0315442. <https://doi.org/10.1371/journal.pone.0315442>
- Linh, H., Truc, D., Binh, N., & Tri, V. (2025). Assessing Water Governance Trends and Challenges at a Local Level - An Application of the OECD Water Governance Framework in Soc Trang Province, Vietnam. *Water*, 17(3), 320. <https://doi.org/10.3390/w17030320>
- Lukas, M. A., Pandic, D. B., Djani, W., & Arjana, I. G. B. (2024). Analysis of water governance in irrigation management institutions in the Bena irrigation area, South Amanuban district, South Central Timor regency. *Journal of Law and Sustainable Development*, 12(3), e2867. <https://doi.org/10.55908/sdgs.v12i3.2867>
- Mariano, R., A. S., Motter, F. R., & Cruz, L., L. (2022). Design and validity of an instrument to assess healthcare professionals' perceptions, behaviour, self-efficacy and attitudes towards evidence-based health practice: I-SABE. *BMJ Open*, 12, e052767. <https://doi.org/10.1136/bmjopen-2021-052767>
- Martínez, R., F. (2010). Los indicadores como herramientas para la evaluación de la calidad de los sistemas educativos. *Sinéctica*, 35, 1-17. <https://sinectica.iteso.mx/index.php/SINECTICA/es/article/view/128/121>
- Maya, J., I. (2024). Using stakeholder network analysis to enhance the impact of participation in water governance. *Humanities and Social Sciences Communications*, 11, 1-6. <https://doi.org/10.1057/s41599-024-02958-x>
- Mubiri, P., Ssengooba, F., O'byrne, T., Aryajja-Keremani, A., Namakula, J., Chikaphupha, K., Aikins, M., Martineau, T., & Vallières, F. (2024). A new scale to assess health-facility level management: the development and validation of the facility management scale in Ghana, Uganda, and Malawi. *BMC Health Services Research*, 24, 371. <https://doi.org/10.1186/s12913-024-10781-y>
- Müller, R., & Lecoivre, L. (2014). Operationalizing governance categories of projects. *International Journal of Project Management*, 32(8), 1346-1357. <https://doi.org/10.1016/j.ijproman.2014.04.005>
- Navarro-Frómata, A. E., Herrera-López, H., Castro-Bravo, C. (2020). Irrigation Water Challenges: A Study Case in the State of Puebla, Mexico. In: Otazo-Sánchez, E., Navarro-Frómata, A., Singh, V. (eds.) "Water Availability and Management in Mexico". Water Science and Technology Library, Vol. 88. Springer. https://doi.org/10.1007/978-3-030-24962-5_12
- Nelson, T., Poleacovschi, C., Weems, C., Ikuma, K., García, I., & Rehmann, C. (2024). Navigating end-user perceptions: development and initial psychometric properties of a water quality perception scale. *Frontiers in Water*, 6, 1357921. <https://doi.org/10.3389/frwa.2024.1357921>
- Nkonyani, H., Gambo, B., Mourad, K., Rilwanu, T., & Berndtsson, R. (2024). Indigenous Knowledge in Watershed Management: The Case of the Mara River Basin, Tanzania. *Water*, 17(1), 63. <https://doi.org/10.3390/w17010063>
- Niederberger, M., & Spranger, J. (2020). Delphi technique in health sciences: a map. *Frontiers in Public Health*, 8, 457. <https://doi.org/10.3389/fpubh.2020.00457>
- Norberto-Cárdenas, N., Robles-Cuevas, H. O., Olvera-Robles, D., Ruiz-Canizales, R., & Nettel-Barrera, A. del C. (2024). Perspectiva jurídica del derecho al agua, la gestión hídrica y las concesiones en México. *DIXI*, 27(1), 1-30. <https://doi.org/10.16925/2357-5891.2025.01.06>
- OECD [Organisation for Economic Cooperation and Development]. (2018). Implementing the OECD Principles on Water Governance: Indicator Framework and Evolving Practices. OECD Publishing. París, Francia. 34p. <http://dx.doi.org/10.1787/9789264292659-en>
- Pires, A., Morató, J., Peixoto, H., Botero, V., Zuluaga, L., & Figueroa, A. (2017). Sustainability Assessment of indicators for integrated water resources management. *The Science of the total environment*, 578, 139-147. <https://doi.org/10.1016/j.scitotenv.2016.10.217>

- PNUD [Programa de las Naciones Unidas para el Desarrollo]. (2015). Guía para los organismos que vigilan la gestión del agua en El Salvador. Como crecen en transparencia y rendición de cuentas. Programa de las Naciones Unidas para el Desarrollo. Antiguo Cuscatlán, El Salvador. 122p. <https://siwi.org/wp-content/uploads/2016/01/social-audit-manual.pdf>
- Renaud, J., Lacasse, M., Côté, L., Théorêt, J., Rheault, C., & Simard, C. (2020). Psychometric validation of the Laval developmental benchmarks scale for family medicine. *BMC Medical Education*, 21, 357. <https://doi.org/10.1186/s12909-021-02797-3>
- Rosso, R. (2025). On Seven Principles of Water Governance. *Water*, 17(6), 896. <https://doi.org/10.3390/w17060896>
- Sahani, A. K., Gupta, G., Anand, S., Sharma, V. R., Singh, R., Kamil, A., Kumar, H., Gagan, A., Mayala, V. K., Mishra, A. P., Jaiswal, S., & Anand, J. (2025). Indigenous Knowledge and Water Conservation Practices in South Africa: A Systematic Literature Review. *Journal of Environmental & Earth Sciences*, 7(2), 248-261. <https://doi.org/10.30564/jees.v7i2.7988>
- Schneider, F., Bonriposi, M., Graefe, O., Herweg, K., Homewood, C., Huss, M., Kauzlaric, M., Liniger, H., Rey, E., Reynard, E., Rist, S., Schädler, B., & Weingartner, R. (2015). Assessing the sustainability of water governance systems: the sustainability wheel. *Journal of Environmental Planning and Management*, 58(9), 1577-1600. <https://doi.org/10.1080/09640568.2014.938804>
- Sierra-Barón, W., Gómez-Acosta, A., & Quintero, A. (2025). Evidencia de validez y fiabilidad de un instrumento de ahorro de agua en población colombiana. *ÁNFORA*. <https://doi.org/10.30854/anf.v32.n59.2025.1153>
- Sinharoy, S., S., Amelie, C., M. P., Patrick, McManus, S., & Caruso, B. (2021). Development and validation protocol for an instrument to measure women's empowerment in urban sanitation across countries: The Agency, Resources, and Institutional Structures for Sanitation-related Empowerment (ARISE) Scales. *BMJ Open*, 12(2), e053104. <https://doi.org/10.1101/2021.05.04.21256595>
- Suárez, P., K. V. & Obregón, N., N. (2024). Distritos de riego y territorios socioecológicos. *Bitácora Urbano Territorial*, 34(1), 129-139. <https://doi.org/10.15446/bitacora.v34n1.111748>
- Victoria, M. A. (2018). Gobernabilidad y gobernanza del agua como bien común de la naturaleza. *Journal of Law and Sustainable Development*, 6(1), 1-20. <https://doi.org/10.37497/sdgs.v6i1.87>
- Whitley, H. (2024). Exogenous, Endogenous, and Peripheral Actors: A Situational Analysis of Stakeholder Inclusion within Transboundary Water Governance. *Sustainability*, 16(9), 3647. <https://doi.org/10.3390/su16093647>

Bovine respiratory disease and its effects on productive performance indicators and carcass yield

Martínez-Hernández, José M.¹; Barrientos-Morales, M.¹; Olivares-Muñoz, A.¹; Yasser-Alarcón, K.¹; Rodríguez-Andrade, A.²; Valverde-Abarca, A.³; Dominguez-Mancera, B.^{1*}

¹ School of Veterinary Medicine and Animal Science, Academic Group Biotechnology for Animal Production and Health, Universidad Veracruzana, Miguel Ángel de Quevedo and Yáñez Street, s/n, Unidad Veracruzana neighborhood, C.P. 91710, Veracruz, Veracruz, Mexico.

² Department of Chemistry and Biochemistry, National Technological Institute of Mexico, Technological Institute of Veracruz, Miguel Ángel de Quevedo 2779, Formando Hogar neighborhood, C.P. 91897, Veracruz, Veracruz, Mexico.

³ Animal Reproduction Laboratory, School of Agronomy, Research and Development Center for Sustainable Agriculture in the Humid Tropics, Costa Rica Institute of Technology, San Carlos Campus, Alajuela, Costa Rica.

* Correspondence: beldominguez@uv.mx

Citation: Martínez-Hernández, J. M., Barrientos-Morales, M., Olivares-Muñoz, A., Yasser-Alarcón, K., Rodríguez-Andrade, A., Valverde-Abarca, A., & Dominguez-Mancera, B. (2026). Bovine respiratory disease and its effects on productive performance indicators and carcass yield. *Agro Productividad*. <https://doi.org/10.32854/80ey1311>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: November 25, 2025.

Accepted: January 13, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 15-23.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



ABSTRACT

Objective: To evaluate the impact of bovine respiratory disease (BRD) on productive performance indicators and hot carcass yield in feedlot cattle raised under intensive tropical production conditions.

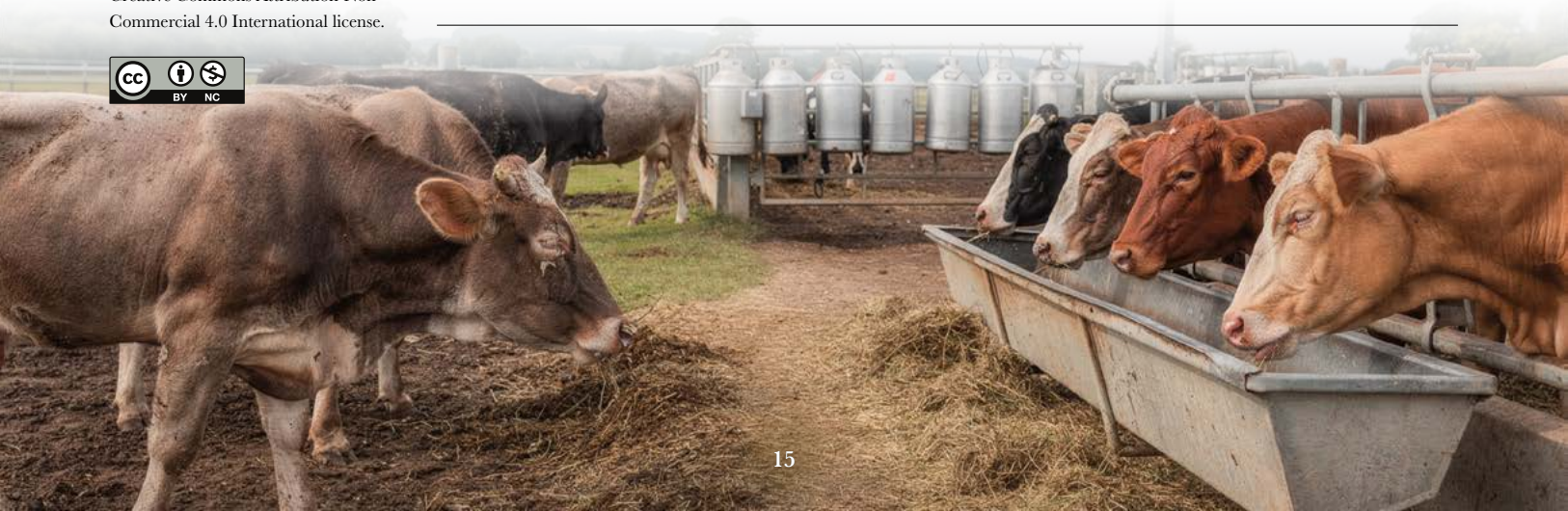
Design/methodology/approach: A total of 1,378 cattle were classified into three groups: animals without clinical signs of BRD, animals with one clinical event, and animals with two events during the fattening period. An ANCOVA model was applied using arrival weight as a covariate, followed by Fisher's LSD test for multiple comparisons. Logistic regression was used to estimate the probability of presenting BRD as a function of hot carcass yield (%).

Results: Cattle experiencing one or two BRD episodes showed significant decreases ($p < 0.05$) in average daily feed intake, daily weight gain, total weight gain, final live weight, and feed efficiency. Hot carcass weight and carcass yield also declined progressively as the number of BRD episodes increased. Logistic regression revealed a negative association between carcass yield and the probability of BRD occurrence, with stronger effects observed in cattle that experienced two clinical events.

Limitations on study/implications: The study was conducted in a single feedlot operation, limiting the generalizability of the findings. Further research in different production systems and climatic regions is recommended to strengthen external validity.

Findings/conclusions: BRD exerts a clear and cumulative negative impact on cattle growth performance and carcass yield. These findings highlight the need for strengthened preventive health programs, early diagnostic tools, and improved management practices to mitigate the effects of BRD in tropical feedlot systems.

Keywords: feedlot cattle; BRD; carcass yield; productive performance; logistic regression.



INTRODUCTION

Bovine respiratory disease (BRD) represents the condition with the greatest economic and productive impact on beef cattle production worldwide and in Mexico (Snowder *et al.*, 2007; Rodríguez-Castillo *et al.*, 2017). Its relevance is not limited to the high morbidity and mortality it causes, but also to the substantial subclinical losses associated with reduced average daily gain (ADG) and feed efficiency, and deterioration of carcass yield and quality (Blakebrough-Hall *et al.*, 2020; Fernandes *et al.*, 2025). BRD is a multifactorial syndrome involving the interaction of infectious agents, environmental and management factors, and animal-related characteristics, which together determine the clinical and subclinical expression of the disease (Taylor *et al.*, 2010; Blakebrough-Hall *et al.*, 2022).

BRD involves the synergistic interaction of respiratory viruses, including bovine herpesvirus type 1 (BoHV-1), bovine viral diarrhoea virus (BVDV), bovine respiratory syncytial virus (BRSV), parainfluenza virus type 3 (PI3), and bovine respiratory coronavirus, as well as opportunistic bacteria such as *Mannheimia haemolytica*, *Pasteurella multocida*, *Histophilus somni*, *Mycoplasma bovis*, and *Trueperella pyogenes* (Taylor *et al.*, 2010; Fernandes *et al.*, 2025; Monge-Navarro *et al.*, 2025; Pratelli *et al.*, 2024). Viral infections cause epithelial damage and impair mucociliary clearance, facilitating deep bacterial invasion that results in fibrinous bronchopneumonia, lung consolidation, and chronic pulmonary lesions (Taylor *et al.*, 2010; Fernandes *et al.*, 2025).

Recent studies have demonstrated that even small lung consolidation lesions ($\geq 1 \text{ cm}^2$), detected by thoracic ultrasonography in calves at weaning, are associated with significant reductions in early growth and persistent effects on carcass quality, particularly reduced marbling scores (Fernandes *et al.*, 2025). Persistent lung consolidation has also been linked to increased susceptibility to secondary infections and systemic effects, including alterations in the hepatic microbiota, although without conclusive evidence of profound dysbiosis (Fernandes *et al.*, 2025).

BRD shows higher prevalence during the receiving and adaptation phases in feedlot systems, especially when animals are exposed to multiple stressors. These include long-distance transportation, commingling of cattle from different sources, abrupt changes in temperature and humidity, overcrowding, inadequate handling, dehydration, and sudden dietary changes (Madureira-Ferreira *et al.*, 2024). In tropical and subtropical regions, high ambient temperature and humidity contribute to immunosuppression and enhance environmental pathogen survival, thereby increasing the risk of disease outbreaks (Pratelli *et al.*, 2024).

Cattle affected by BRD exhibit reduced ADG, lower feed intake and nutrient utilization, extended finishing periods, and poorer feed conversion efficiency (Blakebrough-Hall *et al.*, 2020; Blakebrough-Hall *et al.*, 2022; Wilson *et al.*, 2017). Reported reductions in ADG range from 0.11 to 0.14 kg/day in calves with early lung consolidation (Sáadatnia *et al.*, 2023; Fernandes *et al.*, 2025), while decreases of up to 24 kg in carcass weight have been observed in cattle repeatedly treated for BRD (Wilson *et al.*, 2017).

The impact on carcass traits includes significant reductions in marbling score, ribeye area, and hot carcass weight, as well as a higher proportion of carcasses classified in lower quality categories (Fernandes *et al.*, 2025; Blakebrough-Hall *et al.*, 2020). In addition,

chronic lung lesions identified at slaughter have been associated with reduced carcass yield, metabolic impairment, and increased likelihood of viscera condemnation (Fernandes *et al.*, 2025). Therefore, the objective was to evaluate, in an intensive tropical feedlot production unit, the effect of BRD on key productive performance indicators and hot carcass yield.

MATERIALS AND METHODS

Study area

The study was conducted in a livestock production unit (LPU) located in the central region of the state of Veracruz, Mexico. The climate of the area is classified as Aw2 (warm sub-humid climate) according to the Köppen-Geiger classification (Beck *et al.*, 2018; Vidal-Zepeda, 2005). Mean annual temperature ranges from 22 to 26 °C. From May to September, the region experiences intense rainfall and tropical storms, with annual precipitation reaching up to 1,500 mm, concentrated during the summer months. Predominant northerly winds occur from October to March.

The sampling period extended from January 2023 to June 2024.

Animals and data collection

A simple random sampling design was applied, comprising 5% of the monthly cattle population of the LPU, equivalent to approximately 82 animals per month (n=1,378). Data for the present study were obtained in situ through clinical evaluation of animals and from the daily production records of the LPU, including dates, live weights, and feeding information. Data on hot carcass yield were obtained from slaughterhouse records where the evaluated animals were processed.

Variables evaluated

The dependent variables analyzed were: live weight at arrival to the LPU (kg), time to first antimicrobial treatment following clinical diagnosis of BRD (days), time to second antimicrobial treatment following clinical diagnosis of BRD (days), average daily feed intake (kg), duration of the fattening period (days), final live weight at the end of the fattening period (kg), total feed intake during the fattening period (kg), total weight gain (kg), average daily gain (kg/day), feed conversion ratio (kg of feed/kg of live weight gain), and hot carcass yield (kg and %).

Experimental grouping

Independent variables were defined according to the clinical health status of the animals during the fattening period:

- Group 1: Animals without clinical signs of BRD (fever, cough, epiphora, nasal discharge, tachypnea) throughout the entire fattening period in the LPU.
- Group 2: Animals that exhibited clinical signs of BRD on one occasion during their stay in the LPU and received treatment.
- Group 3: Animals that exhibited clinical signs of BRD on two separate occasions during the fattening period and received treatment.

Statistical analysis

Data were analyzed using analysis of covariance (ANCOVA), where the main factor was health status group and arrival live weight was included as a covariate. The statistical model used was:

$$Y_{ij} = \mu + \tau_i + \beta(x_{ij} - \bar{X}) + \varepsilon_{ij}$$

where: Y_{ij} is the response variable; μ is the overall mean; τ_i is the effect of the i -th group ($i=1, 2, 3$); β is the regression coefficient for the covariate, x_{ij} is the arrival weight of the j -th observation in the i -th group, \bar{X} is the mean arrival weight, and ε_{ij} is the random error assumed to be normally distributed $[N(0, \sigma^2)]$.

Multiple comparisons among group means were performed using Fisher's least significant difference (LSD) test ($p < 0.05$). All statistical analyses were conducted using STATISTICA v10 (2011).

Additionally, logistic regression analysis was performed to estimate the probability of animals having experienced one or two BRD clinical events as a function of hot carcass yield (%). The logistic regression model was expressed as:

$$\log\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X$$

where: P represents the probability of BRD occurrence; β_0 is the intercept; β_1 is the slope coefficient; X corresponds to hot carcass yield (%).

RESULTS AND DISCUSSION

The analysis included a total of 1,378 cattle distributed into three groups according to the presence of clinical signs compatible with bovine respiratory disease (BRD): animals that remained clinically healthy throughout the fattening period ($n=1,062$), animals that experienced one clinical event ($n=204$), and animals that experienced two clinical events ($n=114$). Significant differences ($p < 0.05$) were detected among groups for all productive variables evaluated (Table 1).

Healthy animals exhibited the highest values for growth performance and feed efficiency indicators, whereas cattle that experienced two BRD events showed the lowest values. Live weight at arrival to the LPU differed significantly among groups ($p=0.001$), with mean values of 288.69 ± 1.58 kg for healthy animals, 273.22 ± 3.27 kg for animals with one BRD event, and 255.42 ± 4.04 kg for animals with two BRD events. These initial differences were consistently reflected in productive performance throughout the fattening period.

Average daily feed intake decreased progressively as the number of BRD clinical events increased ($p=0.001$). This reduction was accompanied by a significant decline in average daily gain, which averaged 1.22 ± 0.01 kg/day in healthy animals, 1.15 ± 0.01 kg/day in animals with one BRD event, and 1.04 ± 0.02 kg/day in animals with two BRD events.

Table 1. Productive performance indicators of healthy cattle and cattle that showed clinical signs of bovine respiratory disease (BRD) on one or two occasions during the fattening period in the livestock production unit.

Dependent variables	Healthy animals (N=1,062)	Animals affected once (N=204)	Animals affected twice (N=114)	p-value
Live weight at arrival to the LPU (kg)	288.69±1.58 ^c	273.22±3.27 ^b	255.42±4.04 ^a	0.001
Time to treatment application (days)	***	19.50±1.71	15.97±2.43	***
Average daily feed intake (kg)	9.40±0.01 ^c	9.36±0.04 ^b	9.09±0.05 ^a	0.001
Duration of the fattening period (days)	196.64±0.99 ^a	194.50±2.27 ^a	209.66±3.05 ^b	0.001
Final live weight (kg)	518.00±1.51 ^c	508.00±3.46 ^b	499.93±4.66 ^a	0.001
Total feed intake (kg)	1830.00±8.87 ^a	1810.46±20.34 ^a	1889.39±27.34 ^b	0.001
Total weight gain (kg)	234.30±1.51 ^b	224.30±3.46 ^{ab}	216.23±4.66 ^a	0.001
Average daily gain (kg/day)	1.22±0.01 ^c	1.15±0.01 ^b	1.04±0.02 ^a	0.001
Feed conversion ratio (kg of feed/kg of live weight gain)	8.20±0.07 ^a	8.64±0.16 ^{ab}	9.31±0.22 ^b	0.001
Hot carcass weight (kg)	310.04±0.97 ^c	300.98±2.22 ^b	291.09±2.99 ^a	0.001
Hot carcass yield (%)	59.89±0.10 ^c	59.30±0.23 ^b	58.24±0.31 ^a	0.001

^{a, b, c} Different superscript letters within the same row indicate significant differences among groups (Fisher's LSD test, $p < 0.05$).

Similarly, feed conversion ratio deteriorated significantly ($p=0.001$), reaching values of 8.20 ± 0.07 , 8.64 ± 0.16 , and 9.31 ± 0.22 kg of feed per kg of live weight gain for Groups 1, 2, and 3, respectively.

Final live weight at the end of the fattening period also decreased significantly in association with BRD occurrence ($p=0.001$). Consequently, marked differences were observed in hot carcass yield. Healthy animals achieved a mean carcass yield of $59.89 \pm 0.10\%$, whereas animals with one and two BRD events recorded yields of $59.30 \pm 0.23\%$ and $58.24 \pm 0.31\%$, respectively ($p=0.001$). In addition, hot carcass weight declined significantly with increasing disease recurrence, with values of 310.04 ± 0.97 kg for healthy animals, 300.98 ± 2.22 kg for animals with one BRD event, and 291.09 ± 2.99 kg for animals with two BRD events.

Logistic regression analysis (Table 2) indicated that hot carcass yield was negatively associated with the probability of experiencing a BRD clinical event. For animals with one BRD event, the model showed a negative slope ($B1 = -0.0811$; $p=0.0001$), indicating that lower carcass yield percentages were associated with increased probability of disease. This effect was more pronounced in animals with two BRD events ($B1 = -0.1084$; $p=0.0001$). Odds ratio estimates confirmed this relationship, showing that for each one-percentage-point decrease in hot carcass yield, the probability of having experienced one or two BRD events increased by 7.8% and 10.3%, respectively.

Figure 1 illustrates the negative relationship between hot carcass yield and the probability of BRD occurrence, showing that disease probability increased as carcass yield decreased, with a steeper slope observed in animals that experienced two clinical events. Within the biological window of 40–70%, a clear separation between both curves was observed, confirming the sensitivity of carcass yield as a variable associated with the clinical history of BRD.

Table 2. Logistic regression estimates for the probability of showing clinical signs of bovine respiratory disease (BRD) on one or two occasions in relation to hot carcass yield (%).

N= 1378	Animals affected once (n=204)		Animals affected twice (n=114)	
	Intercept B ₀	Slope B ₁	Intercept B ₀	Slope B ₁
Estimate	3.6072	-0.0811	4.0048	-0.1084
Standard error	1.1183	0.0188	1.4157	0.0241
t-value (1376)	3.2255	-4.3029	2.8289	-4.4987
p-value	0.0013	0.0001	0.0047	0.0001
95% CI (lower)	1.4133	-0.1180	1.2276	-0.1557
95% CI (upper)	5.8010	-0.0441	6.7820	-0.0611
Odds ratio (per unit change)	36.8621	0.9221	54.8621	0.8973
95% CI (lower)	4.1096	0.8887	3.4132	0.8559
95% CI (upper)	330.6413	0.9569	881.8292	0.9407

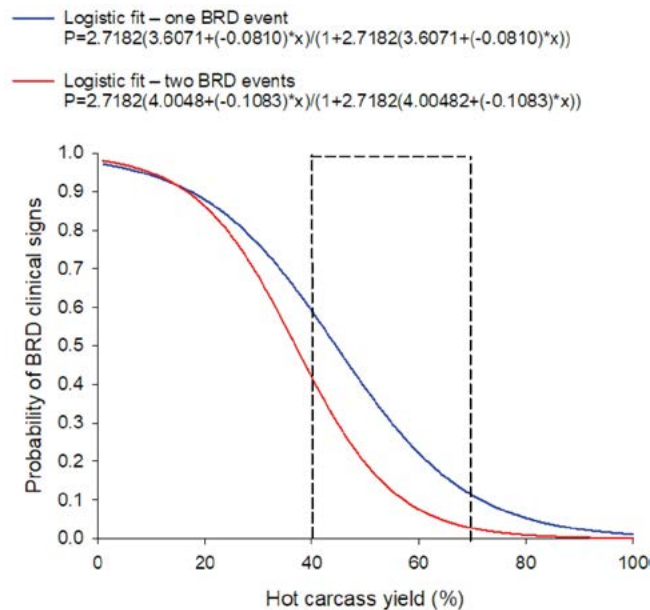


Figure 1. Logistic regression analysis showing the probability of having presented clinical signs of bovine respiratory disease (BRD) as a function of hot carcass yield (%). The blue line represents the logistic regression fit for animals that experienced one clinical event, while the red line represents the fit for animals that experienced two clinical events. The dashed box (40-70%) represents the biological analysis window.

The results of the present study demonstrate that the occurrence of clinical signs compatible with bovine respiratory disease (BRD) has a significant negative impact on productive performance indicators and carcass yield in cattle raised under an intensive feedlot system in the humid tropics of Veracruz. Consistently, animals that experienced one or two BRD clinical events exhibited lower average daily gain, poorer feed conversion efficiency, and reduced carcass weights compared with healthy animals. These findings are consistent with previous reports from intensive production and feedlot systems, where

BRD has been identified as the primary cause of reduced productive efficiency in beef cattle (Blakebrough-Hall *et al.*, 2020; Wilson *et al.*, 2017).

The observed decline in productivity can be explained by the pathophysiology of BRD, which is characterized by pulmonary parenchymal inflammation, reduced effective respiratory capacity, hypoxemia, and alterations in energy metabolism (Taylor *et al.*, 2010). Systemic inflammation is associated with increased maintenance energy requirements, as well as a reduction in voluntary feed intake (Fernandes *et al.*, 2025). These mechanisms are consistent with the findings of the present study, in which average daily feed intake decreased progressively as animals experienced one or more BRD clinical events. Similar patterns have been reported by Sáadatnia *et al.* (2023), who demonstrated that calves with early lung consolidation exhibit reduced feed intake and significant decreases in average daily gain.

The reduction in final live weight and carcass yield observed in this study agrees with previous reports describing cattle that experienced repeated BRD events. Wilson *et al.* (2017) reported that cattle treated multiple times for BRD exhibited lower carcass weights and reduced deposition of muscle and adipose tissue. Likewise, Fernandes *et al.* (2025) demonstrated that even small lung consolidation lesions can have long-term effects on marbling and carcass classification at slaughter. In the present study, both hot carcass weight and carcass yield percentage decreased significantly as the frequency of BRD clinical events increased, indicating that BRD compromises muscle growth, metabolic efficiency, and the animal's capacity for tissue accretion and carcass development.

Logistic regression analysis provided additional evidence of the association between carcass yield and the probability of disease occurrence. The negative slope coefficients indicate that as carcass yield decreases, the probability that an animal experienced one or two BRD clinical events increases. This pattern is consistent with findings reported by Snowden *et al.* (2007), who identified negative correlations between BRD incidence and carcass traits, and it reinforces the usefulness of carcass yield parameters as indirect indicators of the animal's respiratory health history.

The greater productive impact observed in animals that experienced two BRD events suggests that disease recurrence has a cumulative effect on performance. This finding is in agreement with Blakebrough-Hall *et al.* (2022), who reported that the duration and repetition of BRD events increase the likelihood of residual lung damage and amplify variability in productive responses. In addition, studies conducted in Mexico have documented that long-distance transportation, thermal stress, and commingling of animals from different origins increase BRD morbidity and directly affect feedlot efficiency (Rodríguez-Castillo *et al.*, 2017; Monge-Navarro *et al.*, 2025). These factors are particularly relevant in tropical production systems, where environmental conditions may further exacerbate cattle susceptibility to respiratory disease.

The present study also confirms that feed conversion efficiency is compromised in animals with a history of BRD. Epidemiological studies have shown that BRD alters protein and energy metabolism by diverting nutrients toward immune responses, thereby limiting growth efficiency (Madureira-Ferreira *et al.*, 2024). This reduced metabolic efficiency

constrains the animal's ability to fully recover productive performance following a clinical disease event.

Finally, although this study was conducted in a single livestock production unit, the results are consistent with both international and national reports, suggesting that BRD is a key determinant of productive performance and carcass economic value in beef cattle systems in the Mexican tropics. Future studies should incorporate physiological, environmental, and genetic variables to better model individual disease risk and to develop more precise mitigation and prevention strategies.

CONCLUSIONS

Bovine respiratory disease (BRD) significantly affects productive performance and carcass yield in feedlot cattle, as animals that experienced one or two clinical events exhibited lower average daily gain, poorer feed conversion efficiency, and reductions in both hot carcass weight and yield. These negative effects became more pronounced as the recurrence of clinical disease increased. The negative association observed between carcass yield and the probability of BRD occurrence confirms that the disease exerts a direct and cumulative impact on productive efficiency. Therefore, these findings highlight the need to strengthen preventive strategies, early diagnostic approaches, and health management practices in intensive feedlot systems operating under tropical conditions.

ACKNOWLEDGEMENTS

The authors thank the livestock production unit for providing access to the animals for in vivo clinical evaluations and for granting access to the production database used in this study. Appreciation is also extended to the federally inspected slaughterhouse (TIF) for facilitating the evaluation of hot carcass yield.

REFERENCES

- Beck, H., Zimmermann, N., McVicar, T., et al. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5, 180214. <https://doi.org/10.1038/Sdata.2018.214>
- Blakebrough-Hall, C., Hick, P., Mahony, T. J., & González, L. A. (2022). Factors associated with bovine respiratory disease case fatality in feedlot cattle. *Journal of Animal Science*, 100(1), skab361. <https://doi.org/10.1093/jas/skab361>
- Blakebrough-Hall, C., McMeniman, J. P., & González, L. A. (2020). An evaluation of the economic effects of bovine respiratory disease on animal performance, carcass traits, and economic outcomes in feedlot cattle defined using four BRD diagnosis methods. *Journal of Animal Science*, 98(2), skaa005. <https://doi.org/10.1093/jas/skaa005>
- Fernandes, I. L. B., Cantor, M. C., Fonseca, A., Ganda, E., & Felix, T. L. (2025). The association of lung consolidation in beef×dairy cattle at weaning with feedlot growth performance, carcass characteristics, liver health, and liver microbiome diversity. *Journal of Animal Science*, 103, skaf358. <https://doi.org/10.1093/jas/skaf358>
- Madureira Ferreira, M., Santos, B., Skarbek, A., Mills, C., Thom, H., Prentice, D., McConnel, C., & Leal Yepes, F. A. (2024). Bovine Respiratory Disease (BRD) in Post-Weaning Calves with Different Prevention Strategies and the Impact on Performance and Health Status. *Animals*, 14(19), 2807. <https://doi.org/10.3390/ani14192807>
- Monge-Navarro, F. J., Gaxiola Camacho, S. M., López Valencia, G., Trasviña Muñoz, E., Castro Del Campo, N., & Herrera Ramírez, J. C. (2025). Molecular follow-up study on the presence of bovine respiratory coronavirus in feedlot cattle in Northwest Mexico. *Revista Mexicana De Ciencias Pecuarias*, 16(3), 661-676. <https://doi.org/10.22319/rmcp.v16i3.6681>
- Pratelli, A., Cirone, F., Mountricha, M., & Padalino, B. (2024). Editorial: Respiratory diseases and management in livestock. *Frontiers in Veterinary Science*, 11, 1367128. <https://doi.org/10.3389/fvets.2024.1367128>

- Rodríguez-Castillo, J. L., Valencia, G. L., Navarro, F. J., Basulto, G. E., Hori-Oshima, S., Cueto-González, S. A., Mora-Valle, A. D., Real, L. M., Tinoco-Gracia, L., & Rentería-Evangelista, T. B. (2017). Detection and economic impact related to bovine respiratory disease, shrink, and traveling distance in feedlot cattle in Northwest Mexico. *Turkish Journal of Veterinary & Animal Sciences* 41(2): 294-301. <https://doi.org/10.3906/vet-1603-9>
- Sáadatnia, A., Mohammadi, G. R., Azizzadeh, M., Mirshahi, A., Mohieddini, A. A., & Buczinski, S. (2023). Effect of ultrasonographic lung consolidation on health and growth in dairy calves: A longitudinal study. *Journal of Dairy Science*, 106(11), 8047-8059. <https://doi.org/10.3168/jds.2023-23296>
- Snowder, G. D., Van Vleck, L. D., Cundiff, L. V., Bennett, G. L., Koohmaraie, M., & Dikeman, M. E. (2007). Bovine respiratory disease in feedlot cattle: phenotypic, environmental, and genetic correlations with growth, carcass, and longissimus muscle palatability traits. *Journal of Animal Science*, 85(8), 1885-1892. <https://doi.org/10.2527/jas.2007-0008>
- Taylor, J. D., Fulton, R. W., Lehenbauer, T. W., Step, D. L., & Confer, A. W. (2010). The epidemiology of bovine respiratory disease: What is the evidence for predisposing factors? *The Canadian veterinary journal = La revue veterinaire canadienne*, 51(10), 1095-1102.
- Vidal-Zepeda, R. (2005). Las Regiones Climáticas de México. Instituto de Geografía UNAM. Pp. 210
- Wilson, B. K., Step, D. L., Maxwell, C. L., Gifford, C. A., Richards, C. J., & Krehbiel, C. R. (2017). Effect of bovine respiratory disease during the receiving period on steer finishing performance, efficiency, carcass characteristics, and lung scores. *The professional animal scientist*, 33(1), 24-36. <https://doi.org/10.15232/pas.2016-01554>

Evaluation of factors affecting milk production and composition in dual-purpose systems

Retureta-González, Cynthia O.¹; Cervantes-Acosta, Patricia¹; Hernández-Beltrán, Antonio¹; Juárez-Lagunes Francisco I.¹; Hernández, Erika A.²; Inurreta-Aguirre, Héctor D.³; Vega-Murillo, Vicente E.^{1*}

¹ Universidad Veracruzana, Facultad de Medicina Veterinaria y Zootecnia, Miguel Ángel de Quevedo S/N, esq. Yáñez, Veracruz, Veracruz, México, C.P. 91710.

² Tecnológico Nacional de México, Instituto Tecnológico Superior de Tantoyuca. Desviación Lindero Tametate S/N, La Morita, Tantoyuca, Veracruz, México, C.P. 92100.

³ Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Cotaxtla. Carretera Veracruz-Córdoba, km 34.5, Medellín de Bravo, Veracruz, México, C.P. 91700.

* Correspondence: vvega@uv.mx

ABSTRACT

Objective: This study aimed to evaluate the genetic and environmental effects on milk production and composition in dual-purpose cows in the Veracruz tropics.

Methodology: A population of 79 cows grouped by crossbreeds in different proportions of Zebu×Holstein (17), Zebu×Swiss (50), and Zebu×Holstein×Swiss (12) was used. Milk samples were collected at 28-day intervals and analyzed using infrared (IR) spectrophotometry (MilkoScan FT-120, A/S FOSS Electric®). Adjusted means were estimated using PROC GLM from SAS®. The fixed effects included in the model were: genotype, herd, season, lactation number, year, and cow identification. The response variables were: lactation duration (days), production (kg), fat, protein, and lactose (%).

Results: The duration of lactation averaged 307 ± 71.95 days, with total production of $1,240 \pm 468.19$ kg. The values for protein, fat, and lactose were 3.18 ± 0.41 , 3.49 ± 0.82 , and 4.42 ± 0.47 , respectively. Significant differences ($p < 0.05$) were found for the effects of year, calving season, and number of calvings on lactation duration (319 ± 6.6 days) during the dry season and total milk production per lactation during the same season ($1,239 \pm 40.6$ kg) by number of calvings. The longest lactation duration was reported in primiparous cows (345 ± 7.5 days). The effect of sampling season on milk composition was significant ($p < 0.05$) in the rainy season for protein (3.4 ± 0.03 %) and fat (3.8 ± 0.08 %).

Study limitations: This study is limited to a dual-purpose production system with crossbred cattle of different racial composition, under the management and environmental conditions of the participating herds.

Conclusions: The results indicate that milk production and composition are influenced by environmental factors and by differences between the groups evaluated.

Keywords: lactation, fat, protein, genetic, environmental.

Citation: Retureta-González, C. O., Cervantes-Acosta, P., Hernández-Beltrán, A., Juárez-Lagunes F. I., Hernández, E. A., Inurreta-Aguirre, H. D., & Vega-Murillo, V. E. (2026). Evaluation of factors affecting milk production and composition in dual-purpose systems. *Agro Productividad*. <https://doi.org/10.32854/yp3g9m20>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: November 17, 2025.

Accepted: January 15, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 25-35.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

It is estimated that by 2050, the world population will reach 9.7 billion, creating a need to increase animal products (UN, 2022). Cow milk production is one of the most important livestock activities worldwide to meet this demand (North *et al.*, 2023).



Mexico ranks 14th worldwide in cow's milk production in 2023, with 13.5 billion liters per year (CANILEC, 2024). This production takes place under diverse agroecological, technological, and socioeconomic conditions (Barrón *et al.*, 2023), which has given rise to three production systems: specialized or intensive, semi-specialized or family-based, and dual-purpose (SDP) (SIAP, 2021; CANILEC, 2024). Among these, SDP is mainly found in the tropical region, mainly in the state of Veracruz, which accounts for 6.1% of national milk production (SIAP, 2024). The tropical zone offers potential for increasing milk production and quality through genetic crossbreeding used in SDP (Quero *et al.*, 2018, INIFAP, 2018). One of the challenges for livestock farming in this area is to identify, analyze, and estimate milk production and quality parameters and compare them with reference values (Loera & Banda, 2017). In this regard, understanding the variability of milk composition and production in SDP cows will allow for the identification of factors that influence their performance, such as agroecological conditions, nutritional management, and milking practices. This will facilitate the design of strategies to improve milk quality, optimize resources, and increase producer profitability, strengthening the dairy sector and promoting sustainability and economic development in rural communities that depend on this system.

Therefore, the objective of this study was to evaluate the genetic and environmental effects on milk production and composition in dual-purpose cows in the Veracruz tropics.

MATERIALS AND METHODS

Study location

The research was conducted with lactating cows from three dual-purpose (DP) dairy herds located in the central region of the state of Veracruz de Ignacio de la Llave, Mexico. Herd 1 was located in the municipality of Cotaxtla (18.83° N, -96.31° W; 116 m above sea level), herd 2 was located in the municipality of Jamapa (18.59° N, -96.15° W; 22 m above sea level), and herd 3 was located in the municipality of Veracruz (19.10° N, -96.12° W; 14 m above sea level). All three herds have a warm subhumid climate (Aw) according to the Köppen classification modified by García (García, 2004).

Study population

A population of 79 crossbred cows in a dual-purpose production system was used. All animals had production and pedigree data. The grouped genotypes were Holstein×Zebu (H/C) crosses (n=17), Brown Swiss×Zebu (S/C) crosses (n=50), and Brown Swiss×Holstein×Zebu (S/H/C) crosses (n=12).

Animal handling

The animals were fed using controlled rotational grazing with grass varieties such as *Digitaria decumbens*, *Brachiaria decumbens*, *Brachiaria brizantha*, *Brachiaria dictyoneura*, *Cynodon nlemfuensis*, *Megathyrsus maximus*, and native grass (*Paspalum* spp. and *Axonopus* spp.). Supplementation consisted of commercial feed containing 18% protein, supplied at milking time (2 kg per cow), in addition to mineral salts (phosphorus 18%, calcium 18%, sodium 5%, magnesium 4.5%) and free access to water.

The recorded production corresponded to milk milked. In the three herds studied, milking management involved restricted suckling of the calves. During the first 60 days of life, the calves were left a quarter of the udder with residual milk and then only residual milk until weaning. It is estimated that the milk consumed by the calf accounts for approximately 17% of total production (Cervantes *et al.*, 2007; Betancourt *et al.*, 2012). Milking was done mechanically once a day, in the morning.

Reproductive management was by direct mating and artificial insemination. In terms of health management, vaccination was carried out twice a year against bovine paralytic rabies and clostridial diseases, as well as annual deworming.

Milk sampling

Milk production for cows in herd 3 was recorded using the milk weighing device on the mechanical milking machine, while for the other two herds it was recorded using a mechanical clock scale. A total of 652 records were obtained for the period from January 2023 to September 2024.

Milk samples were obtained at 28-day intervals using a simple mechanical milking system. In each herd, 100 ml of milk samples, without preservatives, were collected in capped bottles and kept refrigerated (8 °C) until analysis. Each sample was collected individually at the time of milking to exclude possible adulteration with water, in accordance with the parameters established in Mexican Official Standard NOM-155-SCFI-2012 and the methods of the Association of Official Analytical Chemist (AOAC International, 2016).

In order to consider the seasonal effect, the samples were classified into three periods: dry (March to May), rainy (June to November), and windy season (December to February).

Analysis of milk samples

The milk composition analysis was performed in duplicate during the first 24 hours after collection using infrared (IR) spectrophotometry using a MilkoScan FT-120 equipment, A/S FOSS Electric[®]. The values recorded were: milk production (kg), fat (%), protein (%), lactose (%).

Compilation of information on production units and animals used in research

The production units were characterized by recording information on pedigree, genetic group, cow age, number of lactations, milk production, calving date, and days in lactation. The variables under study were: duration of lactation (days), milk production (kg), fat, protein, and lactose (%).

Statistical analysis

SAS (SAS Institute Inc., Cary, NC, USA) version 9.4 (SAS 2024) was used for data exploration and analysis. The response variables were verified to be normally distributed using the Kolmogorov-Smirnov test of the UNIVARIATE procedure.

An analysis of variance was performed using the least squares method through a general linear model, with the GLM procedure including the fixed effects of genetic group, year,

herd, sampling period, calving period, and number of calvings. The duration of lactation was included as a covariate in the corresponding models.

$$Y_{ijklmn} = \mu + a_i + b_j + c_k + d_l + e_m + f_n + g_o + \varepsilon_{ijklmno}$$

Where: $Y_{ijklmno}$ = Duration of lactation (days), Milk production (kg), fat, protein, and lactose (%); μ = Overall average; a_i = i -th genetic group effect; b_j = j -th year effect; c_k = k -th herd effect; d_l = effect l -th sampling period; e_m = m -th effect number calving period; f_n = f -effect: number of calving; g_o = covariate; $\varepsilon_{ijklmno}$ = random error.

The final model included the main effects and interactions that were significant ($P < 0.05$) in preliminary analyses. Fisher's protected LSD test was used to determine statistically significant differences ($P < 0.05$) between the effects considered in the final models. A Pearson correlation analysis was performed using the CORR procedure in SAS[®] (2024) between the concentration of its components and the total milk production variable.

RESULTS AND DISCUSSION

Descriptive statistics

Table 1 shows the average values, number of observations, and descriptive statistics for the animals used in each analysis, by variable analyzed.

The duration of lactation averaged 307 ± 71.95 days, which is higher than the 219 ± 39.6 days reported by Peralta *et al.* (2021) in SDP. This variation may be associated with differences in reproductive management and drying criteria, since in the herds evaluated, cows were dried off upon confirmation of pregnancy, so the duration depended on the open days (Cristóbal *et al.*, 2007; López *et al.*, 2009; Recinos *et al.*, 2017).

The average total production was 1,240 kg, lower than that reported by Magaña *et al.* (2016), who documented an average of 1,490 kg with an average lactation period of 213 days. This difference can be attributed to the fact that, in the study by Magaña *et al.*, the cows had access to forage throughout the year, with irrigation of the pastures, and therefore milk production was not affected by seasonality (Jayasinghe *et al.*, 2024). In terms of composition, the average protein content was 3.18%, fat 3.49%, and lactose 4.42%, which is within the acceptable range according to NOM-155-SCFI-2012. The protein, fat, and lactose values were similar to those reported in previous studies by Cervantes *et al.* (2015) and Juárez *et al.* (2016) under dual-purpose system conditions.

Table 1. Number of observations and descriptive statistics for lactation duration (days), production (kg), protein (%), fat (%), and lactose (%).

Variable	N	Average	SD	Minimum	Maximum
Duration of lactation	480	307	71.95	127	436
Total yield per lactation (kg)	471	1,240	468.19	152.5	2,375.56
Protein	652	3.18	0.41	1.89	5.37
Fat	652	3.49	0.82	1.73	5.95
Lactose	652	4.42	0.47	1.98	5.86

Effects of the model

Table 2 shows the significance level ($Pr > F$) of each fixed effect included model of the variables analyzed.

The genotype showed a highly significant effect only on the duration of lactation. In contrast, the herd influenced total production and fat content ($p < 0.01$) and, to a lesser extent, protein ($p < 0.05$), suggesting differences between production units associated with management, forage availability and quality, and animal variation (Aranguren *et al.*, 2011). The sampling year affected the duration of lactation, total production, and protein ($p < 0.01$), and showed a minor effect on fat ($p < 0.05$), reflecting interannual variation in climatic conditions and/or management practices. The sampling period influenced total production and protein ($p < 0.01$) and fat ($p < 0.05$), while the calving period affected the duration of lactation, total production, and fat ($p < 0.01$), highlighting the role of seasonality on productive response (Calunga *et al.*, 2007). Finally, the number of calvings had a highly significant effect on lactation duration and total production, and a significant effect on fat, which is consistent with the expected physiological variation between primiparous and multiparous cows (Roca *et al.*, 2012).

Table 3 presents the least square means ($\pm SE$) for year, sampling season, and calving season for lactation period and total production per lactation.

Table 2. $Pr > F$ values for the fixed effects included in the models.

Effect	Lactation duration (days)	Total production (kg)	Protein (%)	Fat (%)	Lactose (%)
Genotype	<0.0001**	0.1454	0.3586	0.9560	0.6988
Herd	0.644	<0.0001**	0.0204*	0.0013**	0.0895
Sampling year	<0.0001**	<0.0001**	0.0004**	0.0434*	0.0961
Sampling season	0.0548	0.0009**	<0.0001**	0.0259*	0.0646
Calving season	<0.0001**	<0.0001**	0.1107	0.0051**	0.4943
Calving number	<0.0001**	<0.0001**	0.0650	0.0235*	0.1529

** Highly significant ($p < 0.01$); * Significant ($p < 0.05$).

Table 3. Least square means ($\pm SE$) by year, sampling season, and calving season for lactation period and total milk production per lactation.

Effect	Lactation period (days)	Total milk production per lactation (kg)
Year	2023	321 \pm 6.1 ^a
	2024	283 \pm 5.8 ^b
Sampling period	Dry	297 \pm 6.5 ^a
	Rain	292 \pm 6.0 ^a
	Windy	313 \pm 7.1 ^a
Calving season	Dry	319 \pm 6.6 ^a
	Rain	286 \pm 5.1 ^b
	Windy	297 \pm 6.1 ^b

^{a-c}: Different letters within each column and effect indicate differences ($P < 0.05$).

Differences ($P < 0.05$) were observed in lactation duration and total milk production per lactation associated with year and calving season, as well as differences in milk production by sampling season (Table 3). In 2023, lactation duration was longest (321 ± 6.1), but total production was lower (905 ± 37.4 kg) compared to 2024 (283 ± 5.8 days and $1,323 \pm 36.5$ kg). This demonstrates the impact of analyzing production records for decision-making, as preliminary results for 2023 showed that cows remained in milking for a long time and it was possible to make adjustments to this parameter to optimize the efficiency of the system. The sampling period did not alter the duration of lactation ($P > 0.05$); however, total production was higher during the rainy season ($1,232 \pm 36.9$ kg) than during the dry season and windy season (Table 3), which coincides with the influence of seasonality on forage availability and quality and, therefore, on productive performance (Arias *et al.*, 2008).

In terms of calving season, cows that calved during the dry season had the longest lactation period (319 ± 6.6 days) and highest total production ($1,239 \pm 40.6$ kg) than those that calved during the rainy and windy seasons (Table 3). These results are consistent with those reported by Castillo *et al.* (2017), who mention that cows that calved during the dry season had higher milk production adjusted to 305 days, with almost 150 kg more milk than cows that calved during the rainy season. The timing of calving has an effect on production trajectory, since, as Vélez de Villa (2013) mentions, when calving occurs at least two months before the peak of maximum forage production, cows tend to produce milk fairly uniformly during the first four months of lactation. Table 4 presents the least square means (\pm SE) for genotype, herd, and number of calvings in lactation length and milk production per lactation.

Concerning to the effect of genotype, significant differences were observed in the duration of lactation; cows in the H/C group had the shortest duration (273 ± 11.0 days), compared to the S/C and S/H/C groups (327 ± 8.9 and 339 ± 9.8 days, respectively) (Table 4). However, the results obtained differ from those reported by Ríos *et al.* (2015), who obtained 266.92 ± 61.61 days. This may be largely due to the management practices used in each of the herds in the different studies. There were no significant differences between genotypes ($p < 0.05$) in milk production per lactation.

For the herd effect, significant differences were found in milk production per lactation ($p < 0.05$); herd 3 had the lowest value ($1,168.9 \pm 35$ kg), compared to herds 1 and 2 ($\approx 1,500$ kg) (Table 4). These differences may be due to the quality and availability of feed resources, even though efforts were made to standardize management conditions (Magaña *et al.*, 2016).

With regard to the number of calvings, a clear pattern can be seen: first-calf cows produced less milk (828 ± 47.3 kg), even with more days in lactation (345 ± 7.5 days), compared to cows with two or more calvings (Table 4). As the number of calvings increased, the duration of lactation decreased slightly, while milk production increased, reaching its peak in cows with five or more calvings. These results are consistent with those reported by Calderón *et al.* (2025), who report that first-calf cows had lower milk production compared to cows with two or more calves. This reflects, as mentioned by Salazar *et al.* (2014), that milk production in the first lactation is influenced by the growth rate and age at first calving.

Table 4. least square means (\pm SE) by genotype, herd, and number of calvings for lactation duration and milk production per lactation.

Effect		Duration of lactation (days)	Milk production per lactation (kg)
Genotype	H/C	273 \pm 11.0 ^a	1,191 \pm 49.7 ^a
	S/C	327 \pm 8.9 ^b	1,092 \pm 31.3 ^a
	S/H/C	339 \pm 9.8 ^b	1,058 \pm 46.6 ^a
Herd	1	299 \pm 7.3 ^a	1,498 \pm 44.6 ^a
	2	306 \pm 9.3 ^a	1,501 \pm 56.7 ^a
	3	297 \pm 5.8 ^a	1,168.9 \pm 35.4 ^c
Number of births	1	345 \pm 7.5 ^a	828 \pm 47.3 ^c
	2	267 \pm 8.0 ^b	1,154 \pm 50.2 ^{ab}
	3	301 \pm 6.5 ^c	1,125 \pm 39.7 ^b
	4	300 \pm 8.1 ^c	1,189 \pm 49.8 ^{ab}
	5+	290 \pm 7.7 ^c	1,272 \pm 47.2 ^a

^{abc}: Different letters within each column and effect indicate differences (P<0.05).

Composition

Table 5 presents the least square means (\pm SE) for year, sampling season, calving season, genotype, herd, and number of calvings for protein, fat, and lactose.

Table 5. least square means (\pm SE) by effect for protein, fat, and lactose (%).

Effect		Protein (%)	Fat (%)	Lactose (%)
Year	2023	3.1 \pm 0.03 ^a	3.6 \pm 0.08 ^a	4.4 \pm 0.05 ^a
	2024	3.3 \pm 0.03 ^b	3.8 \pm 0.08 ^b	4.2 \pm 0.04 ^b
Sampling period	Dry	3.1 \pm 0.04 ^a	3.5 \pm 0.08 ^a	4.2 \pm 0.05 ^a
	Rain	3.4 \pm 0.03 ^b	3.8 \pm 0.08 ^b	4.4 \pm 0.04 ^a
	Windy	3.1 \pm 0.04 ^a	3.7 \pm 0.09 ^{ab}	4.3 \pm 0.05 ^a
Calving period	Dry	3.2 \pm 0.04 ^a	3.6 \pm 0.08 ^a	4.3 \pm 0.05 ^a
	Rain	3.1 \pm 0.03 ^a	3.6 \pm 0.07 ^a	4.3 \pm 0.04 ^a
	Windy	3.2 \pm 0.03 ^a	3.8 \pm 0.08 ^b	4.3 \pm 0.05 ^a
Genotype	H/C	3.3 \pm 0.05 ^a	3.7 \pm 0.10 ^a	4.38 \pm 0.06 ^a
	S/C	3.2 \pm 0.03 ^a	3.7 \pm 0.06 ^a	4.32 \pm 0.04 ^a
	S/H/C	3.2 \pm 0.04 ^a	3.7 \pm 0.10 ^a	4.35 \pm 0.06 ^a
Herd	1	3.2 \pm 0.04 ^a	3.5 \pm 0.09 ^a	4.36 \pm 0.05 ^a
	2	3.2 \pm 0.05 ^a	4.0 \pm 0.12 ^b	4.25 \pm 0.07 ^a
	3	3.3 \pm 0.03 ^b	3.6 \pm 0.13 ^a	4.44 \pm 0.04 ^a
Number of births	1	3.2 \pm 0.04 ^a	3.7 \pm 0.10 ^a	4.42 \pm 0.06 ^a
	2	3.2 \pm 0.05 ^a	3.7 \pm 0.11 ^a	4.29 \pm 0.06 ^a
	3	3.2 \pm 0.04 ^a	3.7 \pm 0.08 ^a	4.40 \pm 0.05 ^a
	4	3.3 \pm 0.05 ^b	3.9 \pm 0.10 ^{ab}	4.37 \pm 0.06 ^a
	5 +	3.2 \pm 0.04 ^a	3.5 \pm 0.10 ^a	4.29 \pm 0.06 ^a

^{abc}: Different letters within each column and effect indicate differences (P<0.05).

Regarding to the effect of year, significant differences were observed between 2023 and 2024 for protein, fat, and lactose (Table 5). In 2024, higher values were recorded for protein ($3.3 \pm 0.03\%$) and fat ($3.8 \pm 0.08\%$), while lactose was slightly lower ($4.2 \pm 0.04\%$) compared to 2023. These differences may be related to climatic, nutritional, and management variations between years (Jayasinghe *et al.*, 2024).

In terms of the sampling season, there were significant differences in protein ($3.4 \pm 0.03\%$) and fat ($3.8 \pm 0.08\%$) content during the rainy season compared to the dry and windy season (Table 5). This could be associated with better forage quality and availability, since during the dry season it tends to be more fibrous and less nutritious, which reduces nutrient intake (Bolaños *et al.*, 2011). Similar results were reported by Martínez *et al.* (2020), who observed higher fat values during the rainy season.

As for lactose, no significant differences were found by sampling period ($p > 0.05$). Cervantes *et al.* (2015) reported higher average values under SDP conditions, which may be related to higher lactation production. In general, lactose plays an osmotic role in the mammary gland, regulating water entry into the alveoli and, therefore, the volume of milk secreted (Sadovnikova *et al.*, 2021).

For the effect of calving season, fat was the component significantly affected, with higher content in cows that calved in the windy season ($3.8 \pm 0.08\%$) (Table 5). This behavior may be associated with production volume (dilution effect), in which higher volumes tend to be accompanied by lower fat concentrations and vice versa (Angulo *et al.*, 2009). In this study, total milk production per lactation was lower in the windy season ($1,002 \pm 43.4$ kg) and was associated with higher fat concentration.

No significant differences were observed in terms of genotype, herd, and number of births ($p > 0.05$), which differs from the findings reported by Cervantes *et al.* (2015). This discrepancy could be attributed to the possible genotype \times environment interaction, where the effect of genotype may not manifest itself in the same way under different environmental conditions, especially in tropical regions (Silva *et al.*, 2021).

In relation to the number of calvings, significant differences were observed only in fat ($p < 0.05$): cows at calving 4 had the highest value ($3.9 \pm 0.10\%$), and the content tended to decrease in subsequent calvings (Table 5). This pattern has been reported in cows in tropical grazing systems (Rosendo *et al.*, 2021). Some studies, however, report increases in protein with the number of lactations (Vargas *et al.*, 2016; Heinrichs *et al.*, 2005).

Table 6 shows Pearson's correlations between total milk yield per lactation.

Significant correlations were observed between some milk components (Table 6). Total production showed a weak negative correlation with fat content ($r = -0.114$; $p = 0.004$), while no significant correlations were detected with protein or lactose content. This behavior is consistent with a dilution effect, in which, as milk volume increases, the concentration of certain components may decrease (Vargas *et al.*, 2016). On the other hand, protein was correlated with fat ($r = 0.582$; $p < 0.0001$) and lactose ($r = 0.469$; $p < 0.0001$). Similar results have been reported by Barrientos *et al.* (2015) and Plascencia *et al.* (2021), although with higher magnitudes.

Table 6. Pearson correlations (r) between total lactation yield and milk components ($n=652$).

Variables	r	p
Total production <i>vs.</i> Protein	-0.027	0.4896
Total production <i>vs.</i> Fat	-0.114	0.0038*
Total production <i>vs.</i> Lactose	-0.016	0.6868
Protein <i>vs.</i> Fat	0.582	<0.0001*
Protein <i>vs.</i> Lactose	0.469	<0.0001*
Fat <i>vs.</i> Lactose	0.182	<0.0001*

* Significant correlation ($p < 0.05$).

Taken together, these results suggest that, in addition to production volume, variation in milk components responds to physiological mechanisms of the mammary gland and the availability of substrates for milk synthesis (Rodríguez and Gómez, 2013).

CONCLUSIONS

In dual-purpose systems in the humid tropics, milk production and composition vary depending on environmental effects and animal characteristics. The duration of the lactation and total production were associated with year, sampling season, calving season, genotype, and number of calvings. These sources of variation should be incorporated into the analysis of productive performance for a more accurate interpretation of the results.

REFERENCES

- Angulo, J., Rodríguez, J., & Suárez, H. (2009). Synthesis, composition, and modification of bovine milk fat: A physiological and nutritional approach. *Journal of the Faculty of Veterinary Medicine and Animal Husbandry*, 14(3), 391-400. <https://www.scielo.org.co/pdf/mvz/v14n3/v14n3a10.pdf>
- AOAC International. (2016). Official Method 972.16: Freezing point of milk. In Official methods of analysis of AOAC International (20th ed.). AOAC International.
- Aranguren Méndez, J. A., Villasmil Ontiveros, Y., Yáñez Cuéllar, L., Ochoa Ordaz, G., & Román Bravo, R. (2011). Analysis of milk production at 244 days in dual-purpose cattle with alternate crossbreeding between Holstein and Red Brahman breeds. *Scientific Journal*, 21(1), 1-11. <https://www.redalyc.org/articulo.oa?id=95945988007>
- Arias, R., Mader, T., & Escobar, P. (2008). Climatic factors affecting the productive performance of beef and dairy cattle. *Archives of Veterinary Medicine*, 40(1). <https://doi.org/10.4067/s0301-732x2008000100002>
- Barrientos, J. M. J., Miranda, J. R., Sánchez, C. E. M., Santos, B. H., Gamboa, E. P., Aldapa, C. a. G., Rivera, P. D., & Herman-Lara, E. (2015). Evaluation and classification of the quality of commercial milk consumed in Tuxtepec, Oaxaca, Mexico. *Ecosistemas Y Recursos Agropecuarios*, 2(6), 327-337. <https://doi.org/10.19136/era.a2n6.71>
- Barrón-Bravo, O. G., Avilés-Ruiz, R., Sahagún-Ángel, C. A., Alcalá-Rico, J. S. G. J., Arispe-Vázquez, J., & Garza-Cedillo, R. D. 2023. Characterization of family cattle production units, Llera, Tamaulipas, Mexico. *Abanico Technical Bulletin*, 2, 1-21
- Betancourt López, L., Pareja Mejía, R. I., Conde Pulgarín, A., Castellanos, Á. F., & Moreno Martínez, D. (2012). Nutritional management of commercial zebu calves subjected to restricted suckling and early weaning in the foothills of Casanare. *Revista Ciencia Animal*, 1(5), 21-30.
- Bolaños Aguilar, E., Meléndez Nava, F., Enríquez Quiroz, J., & Esqueda Esquivel, V. (2011). Production and management of tropical forages. Coyoacán, Mexico: National Institute of Forestry, Agricultural and Livestock Research
- Calderón, Rene & Calderón Chagoya, Rene & Utrera, Ángel & Vega-Murillo, Vicente & Hernández López, Carlos & Lagunes, Juvenio. (2025). Milk Production in Dual-Purpose Cattle Systems under a Humid Subtropical Climate Af(c). *Agro Productivity*. 18. 226-232. 10.32854/agrop.v18i2.3261.

- Calunga, M. M., Valdés, J. A. B., Balmaseda, R. A., Viera, R. G., Viera, G. G., & De Oca, R. V. M. (2007). Seasonality in milk production in a cattle herd. *Animal Production Journal*, 19(1). <https://revistas.reduc.edu.cu/index.php/rpa/article/download/3035/2748>
- National Chamber of Milk Industrialists (CANILEC). Dairy Sector Statistics 2011-2021 (2024).
- Castillo, M. Á., Alpizar, A., Padilla, J., and Keim-San, J. (2017). Effect of age at first service, number and season of calving on the behavior of the lactation curve in Jersey cows. *Tropical Animal Nutrition*, 11(2), 1-22.
- Cervantes, A. P.; Hernández B. A.; Domínguez, M. B.; Villagómez, C. J., and Carrasco García, A. A. 2015. Production and composition of bovine milk in tropical conditions: influence of management and genotype. Page 35. Velázquez, O. V.; Castañeda, V. H.; Wolter, W.; Svarc, G.; Bedolla, C. C. and Guerra, E. L. Milk Production and Quality. ISBN: 978-607-737-094-9
- Cervantes, P. A., Luna, M. R., Hernández, A. B., Pérez-Gil, F., Ponce, P. C., & Uffo, O. R. (2007). Genetic polymorphism at the kappa-casein locus in cows of different breeds and crosses in the Mexican tropics. *Revista Salud Animal*, 29(2), 78-84.
- Cristóbal, C. V., Ordaz, R. L., Muñiz, J. G. G., Valverde, R. R., Flores, A. R., & Ordaz, R. L. (2007). Milk production and reproductive behavior of dual-purpose cows consuming tropical forages and concentrates. *Veterinaria*, 38(1), 63-79. <https://www.medigraphic.com/pdfs/vetmex/vm-2007/vm071g.pdf>from climate change. *Environmental Research Letters*, 18(9), 094027.
- García, E. (2004). Modifications to the Köppen climate classification system (to adapt it to conditions in Mexico) (5th ed., corrected and expanded). National Autonomous University of Mexico.
- Heinrichs, J., Jones, C., & Bailey, K. (2005). Milk components: Understanding the causes and importance of milk fat and protein variation in your dairy herd. DAS 05-97. Pennsylvania State University, University Park.
- Hernández, A., & Ponce de León, R. E. (2024). Effect of genetic group and heterosis on productive traits of Holstein crosses with Zebu. *Livestock Research for Rural Development*, 36(1).
- INIFAP. National Institute of Forestry, Agricultural, and Livestock Research. 2018. INIFAP development program. 2018-2030. Greater productivity in harmony with the environment. Mexico City: SAGARPA.
- Jayasinghe, J. M. P., Pembleton, K. G., Donaghy, D. J., Ramilan, T., & Barber, D. G. (2024). Long-term evaluation of pasture production, seasonality, and variability: An application of the DairyMod pasture model for three tropical species. *European Journal of Agronomy*, 156, 127103. <https://doi.org/10.1016/j.eja.2024.127103>
- Jayasinghe, J., Pembleton, K. G., Barber, D. G., Donaghy, D. J., & Ramilan, T. (2024). Modelling of tropical pasture growth using DairyMod: Model parameterisation and validation across multiple environments. *European Journal of Agronomy*, 156, 127146. <https://doi.org/10.1016/j.eja.2024.127146>
- Juárez B., J. M., Díaz R., P., Rodríguez M., J., Martínez S., C. E., Hernández S., B., Ramírez R., E., Torruco U., J. G., & Herman L., E. (2016). Characterization of milk and quality classification using cluster analysis in dual-purpose systems. *Revista Mexicana de Ciencias Pecuarias*, 7(4), 525-537. <https://doi.org/10.22319/rmcp.v7i4.4280>
- Loera, J., & Banda, J. Dairy industry in Mexico: Parameters of milk production and supply of the internal market. *Rev. investig. Altoandín*. [online]. 2017, vol.19, n.4, pp.419-426. ISSN 2313-2957. <http://dx.doi.org/10.18271/ria.2017.317>
- López-Ordaz R, Vite-Cristóbal C, García-Muñiz JG, Martínez-Hernández PA. Reproduction and milk production in cows with different proportions of *Bos taurus* genes. *Arch Zoot* 2009;58(224):683-694.
- Magaña-Monforte, J. G., Osorio, E., Centurión-Castro, F., Segura-Correa, J. C., Aké-López, R., & Aguilar-Pérez, C. F. (2016). Milk production and pregnancy rate of dual-purpose cows in southeastern Mexico. *Live-stock Research for Rural Development*, 26(4).
- Martínez, G. M., Carabajal, R. L., Martínez, F., & Suarez, V. H. (2020). Influence of the seasons on the composition and sanitary quality of bovine milk in the Lerma Valley, Salta. *FAVE Veterinary Sciences Section*, 19(1), 35-39. <https://doi.org/10.14409/favecv.v19i1.9446>
- United Nations. World Population Prospects 2022: Summary of Findings. UN DESA/POP/2022/TR/NO. 3; United Nations: Geneva, Switzerland, 2022.
- North, M. A., Frank, J. A., Ouweneel, B., Trisos, & C. H. (2023). Global risk of heat stress to cattle
- Peralta T, JA, Izquierdo C, Y., Severino L, VH, and Segura C, JC (2021). Milk production of Holstein × Gyr cows in a dual-purpose system in the tropics. *Revista MVZ Córdoba*, 27(1). <https://doi.org/10.21897/RMVZ.2359>
- Quero, A., Enríquez, J., Bolaños, E., and Villanueva, A. 2018. State of the art in research and technological innovation in tropical cattle farming. Chapter II: Forages and grazing in tropical Mexico. Technical book. 2nd Ed. National Council for Science and Technology. Mexico. pp. 66-91.

- Recinos, C. A., Ibáñez, E. M. A., Arce, M. M. O., Garduño, R. G., Rivera, P. D., & Cuellar, J. a. H. (2017). Evaluation of productive and reproductive parameters in a dual-purpose herd in Tabasco, Mexico. *Mexican Journal of Animal Science*, 8(1), 83-91. <https://doi.org/10.22319/rmcp.v8i1.4347>.
- Ríos UA, Hernández HVD, Amezcua MEV, Zárate MJP. Milk production of Simmental × Zebu and Brown Swiss × Zebu cows in a tropical climate. *Agron Mesoam* 2015;26(1):17-25.
- Roca, A. I., González, A., & Vázquez, O. P. (2012). Effect of calving date and number of calvings on milk production and quality in grazing cows. 51st Scientific Meeting of the Spanish Society for the Study of Pastures. Public University of Navarra. Retrieved from <https://academica-e.unavarra.es/entities/publication/ba2f1f12-f71f-46fb-8b0a-c1aa08af38ce>
- Rodríguez, C. E., & Gómez, D. F. (2013). Effect of supplementation with different doses of protected fat on production and compositional parameters of bovine milk. *Tropical Animal Science*, 37(4), 299-310. https://ve.scielo.org/scielo.php?script=sci_arttext&pid=S0798-72692013000400004
- Rosendo-Ponce, A., Sánchez-Gómez, A., Ríos-Ortíz, Á., Torres-Hernández, G., & Becerril-Pérez, C. M. (2021). Milk yield and chemical composition of Lechero Tropical native cows under grazing and supplementation. *Agricultural Science and Technology*, 22(1), e1515. https://doi.org/10.21930/rcta.vol22_num1_art:1515
- Sadovnikova A, Garcia SC, Hovey RC. A Comparative Review of the Cell Biology, Biochemistry, and Genetics of Lactose Synthesis. *J Mammary Gland Biol Neoplasia*. 2021 Jun;26(2):181-196. doi: 10.1007/s10911-021-09490-7. Epub 2021 Jun 14. PMID: 34125364; PMCID: PMC8236053.
- Salazar C, M., G. Castillo B, J. Murillo H, F. Hueckmann V, and J.J. Romero Z. 2014. Effect of age at first calving on first lactation milk yield in Holstein cows from Costa Rican specialized dairy herds. *Open J. Vet. Med.* 4:197-203. doi:10.4236/ojvm.2014.49023
- SAS. SAS/STAT® (versión 9.4) User's guide. Cary, NC: SAS Institute Inc.
- Ministry of Economy. NOM-155-SCFI-2012. Milk, milk formula, and combined milk products, physical and chemical specifications, commercial information, and testing methods. Mexico. 2011.
- SIAP. (2024). Agri-Food and Fisheries Information Service. <https://www.gob.mx/siap/documentos/siacon-ng-161430>
- Silva, D. A., Lopes, P. S., Costa, C. N., Silva, A. A., Silva, H. T., Silva, F. F., Veroneze, R., Thompson, G., & Carvalheira, J. (2021). Genotype by environment interaction for Holstein cattle populations using autoregressive and within- and across-country multi-trait reaction norms test-day models. *Animal*, 15(2), 100084. <https://doi.org/10.1016/j.animal.2020.100084>
- Agricultural, Livestock, and Fisheries Information and Statistics System (SIAP). (2021). Livestock sector statistics. Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food. Mexico.
- Vargas S., D., Murillo H., J., Hueckmann V., F., & Romero Z., J. J. (2016). Fat/protein ratio and urea nitrogen values in milk from dairy cows in the northern region of Alajuela and Heredia, Costa Rica. *Veterinary Sciences*, 34(2), 67-80. <https://doi.org/10.15359/rcv.34-2.1>
- Vargas Sobrado, D., Murillo Herrera, J., Hueckmann Voss, F., & Romero Zúñiga, JJ (2016). Fat/protein ratio and urea nitrogen values in milk from dairy cows in the northern region of Alajuela and Heredia, Costa Rica. *Veterinary Sciences*, 34(2), 67-80. <https://doi.org/10.15359/rcv.34-2.1>
- Vélez de Villa, E. (2013). Environmental factors affecting milk production in cattle under semi-intensive grazing. National University of San Marcos. Retrieved from: <https://www.produccion-animal.com.ar>

Plant selection using a sequential decision algorithm based on an ideotype

Couttolenc-Brenis, Edgar^{1*}; Diaz Padilla, Gabriel¹; Toral-Juárez, Marco A.¹; López Morgado, Rosalio¹

¹ Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP). Centro de Investigación Regional Golfo Centro (CIRGOC). C.E. Cotaxtla/S.E. Teocelo. Xalapa, Veracruz, México, C.P. 91190.

* Correspondence: couttolenc.edgar@inifap.gob.mx

ABSTRACT

Objective: Develop a sequential decision algorithm to select plants in populations without repetitions based on an ideotype, using a logical process that employs everything from spreadsheets to programming languages.

Design/methodology/approach: A sequential algorithm based on conditional logic is proposed that implements a multi-criteria filtering process. The algorithm can be implemented on different numerical analysis platforms as it is based on a sequential logical decision process. To validate its application, a selection was made from a population of 60 coffee plants (*Coffea arabica* L.) of the Sarchimor T5296 variety, using Excel as the platform and the AND function due to its accessibility.

Results: Nine plants were selected that exhibited the desired characteristics of yield, plant height, canopy diameter, bienniality (I), and resistance to orange leaf rust, demonstrating the algorithmic selection capability.

Limitations on study/implications: The method has limitations inherent to its binary sequential design: (1) it does not differentially weight the importance of criteria, (2) it does not consider negative correlations between characters in simultaneous selection, and (3) it depends on thresholds defined *a priori*.

Findings/conclusions: The algorithm made it possible to select plants with behavior similar to or superior to the ideotype in contexts where conventional statistical methods are not applicable because they require replicated experimental designs.

Keywords: Plant breeding, Numerical method, Sequential logic, Phenotypic traits.

Citation: Couttolenc-Brenis, E., Diaz Padilla, G., Toral-Juárez, M. A., & López Morgado, R. (2026). Plant selection using a sequential decision algorithm based on an ideotype. *Agro Productividad*. <https://doi.org/10.32854/zvcy5g05>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: November 26, 2025.

Accepted: January 20, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February, 2026. pp: 37-47.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.

INTRODUCTION

Ideotypes are biological models based on traits like productivity, physiology, and environmental adaptation. These traits help select the best plants for genetic improvement (Donald, 1968; Dickmann *et al.*, 1994; Carbajal-Friedrich and Burgess, 2024). An ideotype helps identify potential parent plants in a population by their phenotype (Gauffreteau, 2018). To use this method, we need to define the desirable traits in plants. These traits relate to production and responses to biotic and abiotic factors (Dickmann *et al.*, 1994). Trials are crucial for studying how a plant population performs and for choosing the



best individuals based on the ideal type criteria through mass selection (Bresseghele and Coelho, 2013). The trials should involve enough plants to find those with the desired traits (Cortina *et al.*, 2013).

However, traditional selection methods can be slow and biased. Many plant breeders perform these tasks by hand, which leads to inefficiencies (Azimzadeh *et al.*, 2010). Researchers have developed various numerical and computational methods to improve this. Hazel's selection indices (1943) assign weights to traits based on their economic importance. Pešek and Baker (1969) focus on desired genetic gain. Mulamba and Mock (1978) suggest a non-parametric index to rank traits' importance. Mendes *et al.* (2009) suggest using standardized trait measurements and choosing those with the best scores. Rocha *et al.* (2018) introduced the FAI-BLUP Index, which selects genotypes close to the ideotype. The MGIDI by Olivoto and Nardino (2021) selects genotypes nearest to ideal values.

In coffee cultivation (*Coffea arabica* L.), the main selection indices are: Mulamba and Mock index, standardized values index, FAI-BLUP Index, and MGIDI (Piza *et al.*, 2023; Berny Mier and Teran *et al.*, 2025). Evaluated traits include: productivity, rust resistance (*Hemileia vastatrix* Berk & Broome), resistance to fruit rot (*Colletotrichum kahawae* J. M. Waller & Bridge), number of empty fruits, cup quality, and size (Mishra, 2019). The implementation of these indices in coffee cultivation typically involves the use of statistical packages such as SAS or R, which need programming knowledge (Rahimi and Debnath, 2023). Specific R packages exist for MGIDI and FAI-BLUP Index (Resende, 2016; Olivoto and Nardino, 2021). Many multivariate selection methods must at least three replicates for each genotype. This is necessary to estimate variance and genetic parameters with precision. This requirement restricts their use in everyday situations: (1) established commercial plantations, (2) germplasm banks with one individual per accession, (3) smallholder populations, and (4) species in domestication.

This paper presents a new algorithm for selecting the best ideotype in populations with limited replicates. The algorithm follows a logical process and works on many platforms, like spreadsheets and programming languages.

MATERIALS AND METHODS

Development of the sequential algorithm

The algorithm uses a sequential filtering process in which each criterion of the ideotype functions as an independent logical filter. A plant is selected when it meets all conditions at the same time (Equation 1).

$$\text{Selected individual} = C1 \text{ AND } C2 \text{ AND } C3... \text{ AND } Ci \quad (1)$$

Where: AND represents the logical conjunction operator; C_i is a condition of the type: C_i : Variable_i θ Threshold_i with $\theta \in \{<, >, \leq, \geq, =\}$ according to the selection criteria established in the ideotype.

To demonstrate its accessibility, it was implemented in Excel[®], although the logical process is platform-independent and can be implemented in any environment that supports conditional operations (R, Python, SAS, database systems, etc.). The logical function used was “AND”, which allows determining whether all the conditions of a test are true. When plants meet all the conditions of the ideotype (phenotypic traits), the function shows the true value of the argument (Equation 2). The variables and parameters (ideotype) used to demonstrate the application of the algorithm were: minimum average yield (X1), bienniality index I (X2), maximum plant height (X3), maximum canopy diameter (X4), and rust resistance index IRs (X5).

$$\text{Selected individual} = \text{AND}(\text{Yield} > X1, I < X2, \text{Height} < X3, \text{canopy} < X4, \text{IRS} < X5) \quad (2)$$

The ideotype for the population of plants of the Sarchimor T5296 variety was defined by two variables related to fruit productivity (yield and bienniality), two related to plant morphology (plant height and canopy diameter), and one related to rust resistance (Figure 1). For productivity, a minimum yield of 4,000 g was considered, and for bienniality,

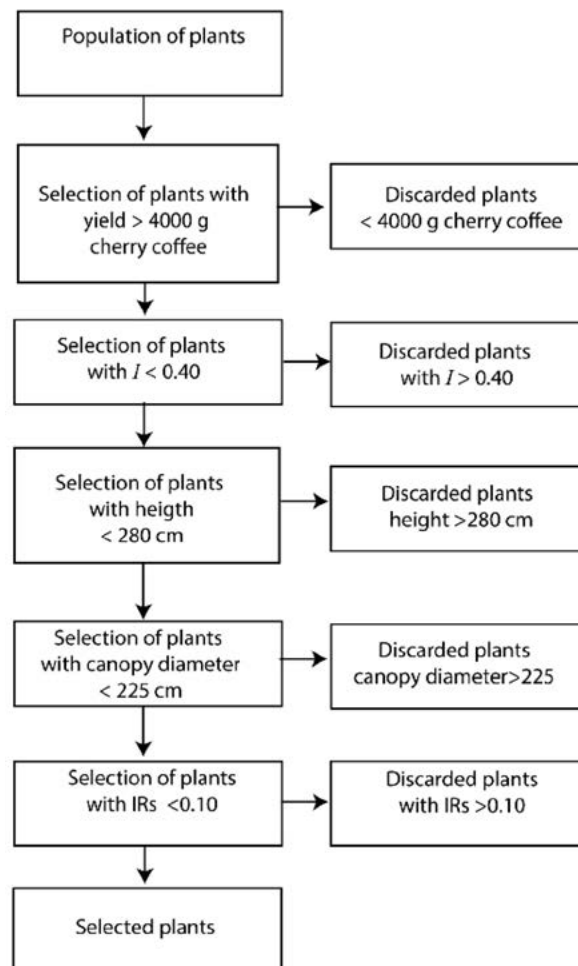


Figure 1. Flowchart for implementing the plant selection algorithm.

the index proposed by Hoblyn *et al.* (1937) with an $I > 0.40$ was considered. In terms of morphology, the aim is to develop compact plants, establishing a maximum height of 280 cm and a maximum canopy diameter of 225 cm. Regarding resistance to *H. vastatrix*, the rust resistance index proposed by Couttolenc-Brenis *et al.* (2023) with an $IRs > 0.1$ was used.

Vegetative material

The algorithm and the Excel[®] function were tested with data collected between 2020 and 2022. This data was from a group of 60 plants of the Sarchimor T5296 variety. This material comes from crossing the Timor Hybrid CIFC 832/2 with Villa Sarchi 971/10. This was done in 1959 at the Coffee Rust Research Center (World Coffee Research, 2019). In 2016, certified seed was acquired from the Los Cafetalones farm in San Juan Acotenango, Guatemala, and in July 2017, the plantation was established at the Teocelo Experimental Site as part of the project “Strategy to strengthen state innovation centers and boost the productivity and quality of Mexican coffee”, under the agreement between INIFAP and AMECAFE.

Location

The plants are in the rust-resistant variety garden, part of the coffee germplasm bank. This is at the Teocelo Experimental Site in Teocelo, Veracruz. The site is located at a latitude of 19° 23' 34.1" N and longitude of 97° 00' 03.5", at an elevation of 1,250 meters above sea level. Annual rainfall is 2,063 mm. The average temperature is 20 °C. The max average reaches 25 °C, and the min average is 14 °C. The soils are from andosol-type volcanic ash (Couttolenc-Brenis *et al.*, 2023).

Variables

In 2021, morphological variables were measured: plant height and canopy diameter. The average yield was obtained during the 2019-2020, 2020-2021, and 2021-2022 harvest cycles. The biennial variation was estimated using the bienniality index proposed by Hoblyn *et al.* (1937), Equation 3, to represent the variation between one harvest and another. The Resistance Index (IRs) to *H. vastatrix* was estimated using Equation 3 (Couttolenc-Brenis *et al.*, 2023).

$$I = \frac{1}{n-1} \sum (R_{T1} - R_{T0}) / R_{T0} + (R_{T2} - R_{T1}) / R_{T1} + \dots (R_{Ti} - R_{Tn}) / R_{Tn} \quad (3)$$

Where: I =Bienniality index; R_{T0} =Yield at time 0; R_{T1} =Yield at time 1; R_{T2} =Yield at time 2; R_{Ti} =Yield at the i th time; R_{Tn} =Yield at the n th time.

$$IRs = (PS \cdot NHI) / (PT \cdot NHT) \quad (4)$$

Where: IRs =Resistance Index; PS =Pustules with sporulation; PT =Total pustules; NHI =Number of infected leaves; NHT =Total number of leaves.

Statistical analysis

To determine if there were significant differences between the observed and estimated variables, a t-test was conducted using the statistical software Infostat[®] (Di Rienzo *et al.*, 2011). The program also provided key statistics, including the mean, standard deviation, and coefficient of variation.

To characterize the population and contextualize the selection results, phenotypic correlation analyses were performed using Pearson's coefficient among the five ideotype variables. Additionally, principal component analysis (PCA) was employed to visualize the multivariate structure of the population and the positioning of the selected plants. Efficiency analysis was conducted by calculating the percentage of plants eliminated at each stage of sequential filtering in R.

RESULTS AND DISCUSSION

The t-test revealed significant differences ($p < 0.05$) among the 60 Sarchimor T5296 plants regarding the observed and estimated variables that define the ideotype. These results indicated that at least one plant may possess the desired traits for selection in the coffee breeding program. Among the five variables, the highest coefficient of variation (CV) was found in IRs at 52.42%, followed by average yield at 34.64%. This suggests that exceptional individuals can be identified within this Sarchimor population for further evaluation in new cultivar development.

Previous studies, such as Cardoso *et al.* (2016), reported yield CVs ranging from 7.68 to 9.32, while rust resistance variables had CVs from 12.79 to 14.67. Botelho *et al.* (2010) found CVs of 28.32 for yield and 38.2 for rust severity in progenies from the Catimor and Icatu cross. However, these studies did not factor in yield variation for genetic improvement, which is determined by the biennial index (I) (Hoblyn *et al.*, 1937; Merga *et al.*, 2023). The Sarchimor T5296 population showed an average I of 0.42, indicating significant biennial variation, compared to 0.31 reported by Merga *et al.* (2023) in a genotype trial in Ethiopia. Some individuals in the population had I values below 0.40, making them candidates for selection.

Phenotypic Correlation

The phenotypic correlation matrix (Figure 2) highlighted significant relationships among five key traits for genetic improvement. The strongest association ($p < 0.001$) was between yield and plant height (0.73), indicating that taller plants tend to be more productive,

Table 1. T-test values to identify significant differences in the variables of the population of Sarchimor T5296

Variable	n	Mean	SD	CV	Min	Max	T	p
Average yield (g)	60	3549.37	1229.44	34.64	624.87	5502.40	22.36	<0.0001
Bienniality index(I)	60	0.42	0.09	20.89	0.34	0.74	37.08	<0.0001
Height (cm)	60	247.78	31.36	12.65	150.00	313.00	61.21	<0.0001
Canopy diameter (cm)	60	192.43	24.51	12.74	115.00	242.50	60.81	<0.0001
Resistance index (IRs)	60	0.06	0.03	51.41	0.02	0.18	15.07	<0.0001

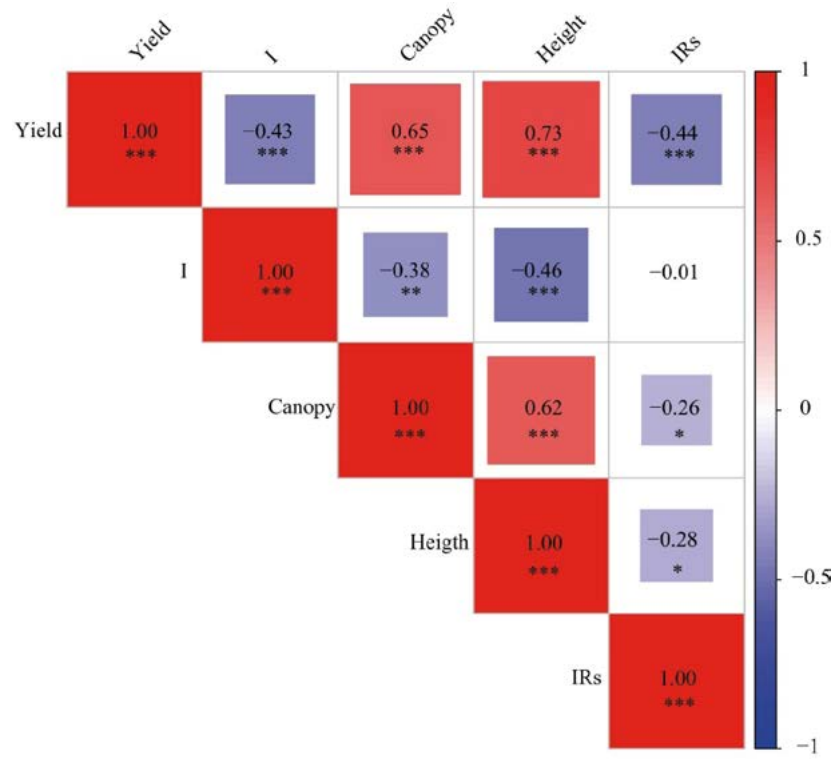


Figure 2. Phenotypic correlations between the variables used to select plants. Asterisks indicate the significance level of the correlation between variables (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

making height a valuable trait for indirect selection. Yield also showed a significant positive correlation ($p < 0.001$) with canopy diameter (0.65), emphasizing that vegetative vigor, reflected in structural dimensions, is vital for productivity. To select materials, one of these variables could be prioritized, or the vigor index proposed by López *et al.* (2021) could be utilized, as both demonstrated a high correlation (0.62, $p < 0.01$).

A notable finding was the negative correlation ($p < 0.05$) between yield and bienniality (-0.43), suggesting that increased biennial expression could affect yield potential, highlighting a critical trade-off for plant breeders (Merga *et al.*, 2023). Additionally, bienniality was negatively associated with IRs at -0.01 , which was not significant. IRs showed a significant negative correlation ($p < 0.001$) with yield (-0.44), indicating that rust resistance negatively impacts productivity, which is why this factor is commonly included in genetic improvement programs (Cardoso *et al.*, 2016; Berny Mier and Teran *et al.*, 2025). In summary, this correlation network informs selection: enhancing vigor (height/diameter) will improve yield, but caution is needed to avoid inadvertently increasing bienniality and maintaining low IR levels.

Implementation of the Sequential Algorithm

Using Excel's "AND" function, the algorithm selected nine plants from the 60 (Table 2). The yield variable eliminated 38 plants, plant height discarded five more, the biennial index excluded four, canopy diameter eliminated four plants, while IRs did not eliminate

Table 2. Characteristics of Sarchimor T5296 plants selected using the algorithm.

Planta	Yield (g)	Height (cm)	I	Canopy diameter (cm)	IRs
14	4388.93	0.37	272	225	0.04
18	4719	0.36	278.5	192.5	0.05
20	4219.87	0.34	249	192.5	0.03
25	5452.6	0.35	244	215	0.02
46	4287.87	0.34	270	162	0.06
47	5502.4	0.38	280	205	0.05
48	4215.47	0.37	262	205	0.08
51	5159.13	0.38	234	216	0.06
53	4524.8	0.37	278.5	182.5	0.05

any (Figure 3). Yield was the most effective variable for discarding plants, followed by height, canopy diameter, and bienniality.

This selection method is straightforward, for having the flexibility to implement it in Excel, though it has limitations compared to more advanced numerical approaches and

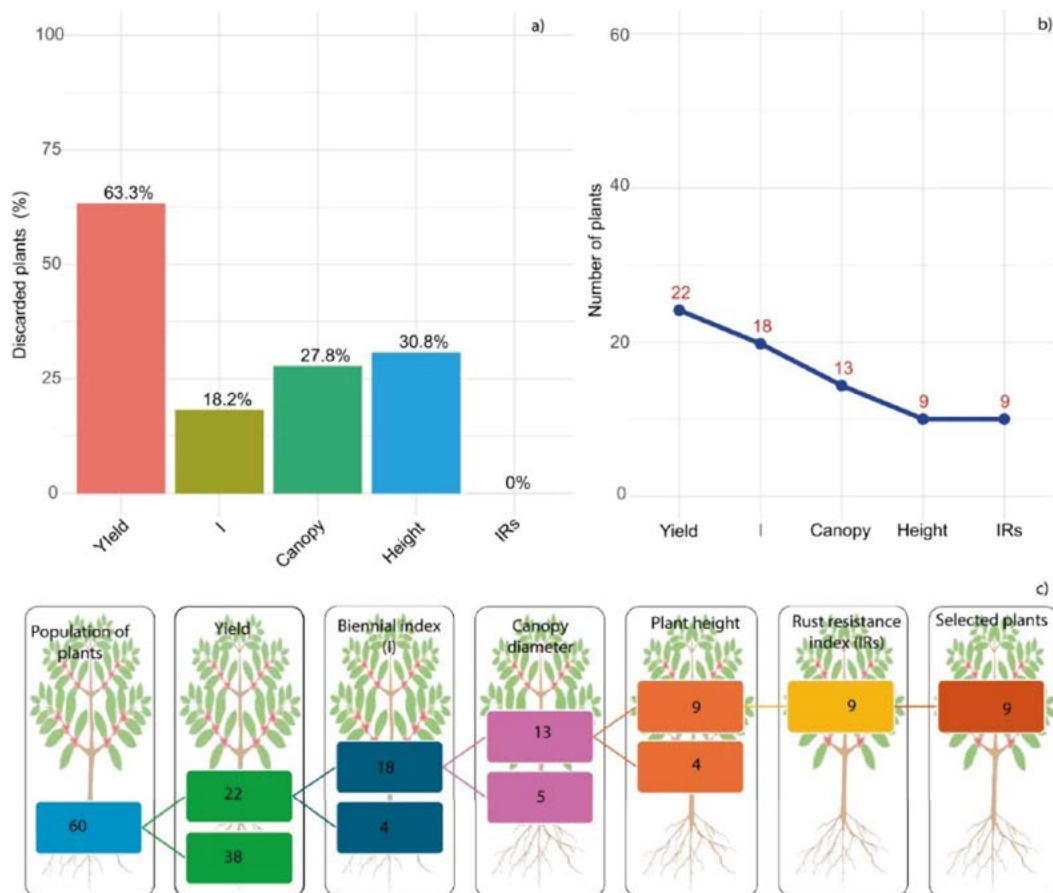


Figure 3. Selection process for the nine individuals with desirable traits for progeny trials. (a) Efficiency of each criterion for discarding plants at each selection stage. (b) Plants remaining selected at each stage. (c) Diagram of the overall selection process, highlighting selected and discarded plants.

specialized software. Azimzadeh *et al.* (2010) suggested using a selection index with a genetic algorithm in MATLAB, which requires knowledge of genetic parameters, complicating its use without prior population information. Alternative methods include multivariate techniques, such as MGIDI proposed by Olivoto and Nardino (2021) or FAI-BLUP by Rocha *et al.* (2018), which also require replicates of each genotype, making them unsuitable for populations without individual replicates, like the one used to validate the proposed sequential selection algorithm.

Another option to the sequential algorithm is developing a selection index using importance coefficients for the evaluated variables. These coefficients can be estimated based on economic importance (Hazel, 1943; Cerón-Rojas *et al.*, 2023) or the desired genetic gain for each trait (Pešek and Baker, 1969), though their application is limited for selecting individuals based on an ideotype (Rodrigues *et al.*, 2017).

In coffee genetic improvement, methods based on multivariate analysis have been employed (Moreira *et al.*, 2022; Paredes-Espinosa *et al.*, 2023; Piza *et al.*, 2023; Berny Mier and Teran *et al.*, 2025; Suela *et al.*, 2025), including the Mulamba and Mock selection index (Piza *et al.*, 2023) and the sum of standardized variables index (Piza *et al.*, 2023). These methods require at least three replicates for each evaluated material, making them unsuitable for selecting individuals from non-replicated populations, unlike the proposed sequential algorithm, which works directly with individual phenotypic values, making it applicable in coffee plantations lacking replicated experimental designs.

Additionally, the proposed method adapts to available resources, from spreadsheets to advanced computational pipelines. While other methods rely on specific computational environments (R packages, SAS), this approach democratizes scientific selection, enabling technicians and producers without advanced statistical training to use it. Each selection criterion is clear and adjustable, allowing for modifications to different conditions and breeding objectives. It also facilitates changes to the ideotype by identifying which criteria are most restrictive in a given population.

Characteristics of the Selected Plants

The mean test (t-test) comparing the nine plants selected by the algorithm revealed significant differences ($p < 0.05$) in each selection attribute (Table 3). The PCA indicated that 76.7% of the variation in the plant population was explained by the first two principal components, with principal component 1 (PC1) accounting for 56.2% and principal component 2 (PC2) accounting for 20.5%. PC1 primarily represented yield ($\cos^2 > 0.81$), height ($\cos^2 > 0.75$), and canopy diameter ($\cos^2 > 0.66$). Bienniality was similarly represented in both components (PC1 $\cos^2 > 0.364$ and PC2 $\cos^2 > 0.365$). Finally, IRs was represented in CP2 ($\cos^2 > 0.64$, Figure 4). The selected plants cluster in the positive quadrants of CP1, with plants 18, 46, 48, 51, and 53 in the positive quadrant of CP2, and plants 14, 47, 20, and 25 in the negative quadrant. All are closely associated with yield, canopy diameter, and height (Figure 4).

Plant 20 exhibited a lower bienniality level (I), a compact shape (combination of canopy diameter and height), and a lower Susceptibility Index (IRs), aligning with the PCA findings, as it was closest to the center among the selected plants (Figure 4). In terms of

Table 3. Comparison of means (t-test) of the selection parameters among the nine plants selected using the algorithm.

Variable	n	Mean	SD	S.E.	CV	T	p(Bilateral)
Yield (g)	9	4718.9	522.11	174.04	11.06	27.11	<0.0001
Height (cm)	9	263.11	16.95	5.65	6.44	46.57	<0.0001
Canopy diameter (cm)	9	199.5	19.42	6.47	9.73	30.82	<0.0001
IRs	9	0.05	0.02	0.01	36.08	8.32	<0.0001
I	9	0.36	0.02	0.01	4.32	69.5	<0.0001

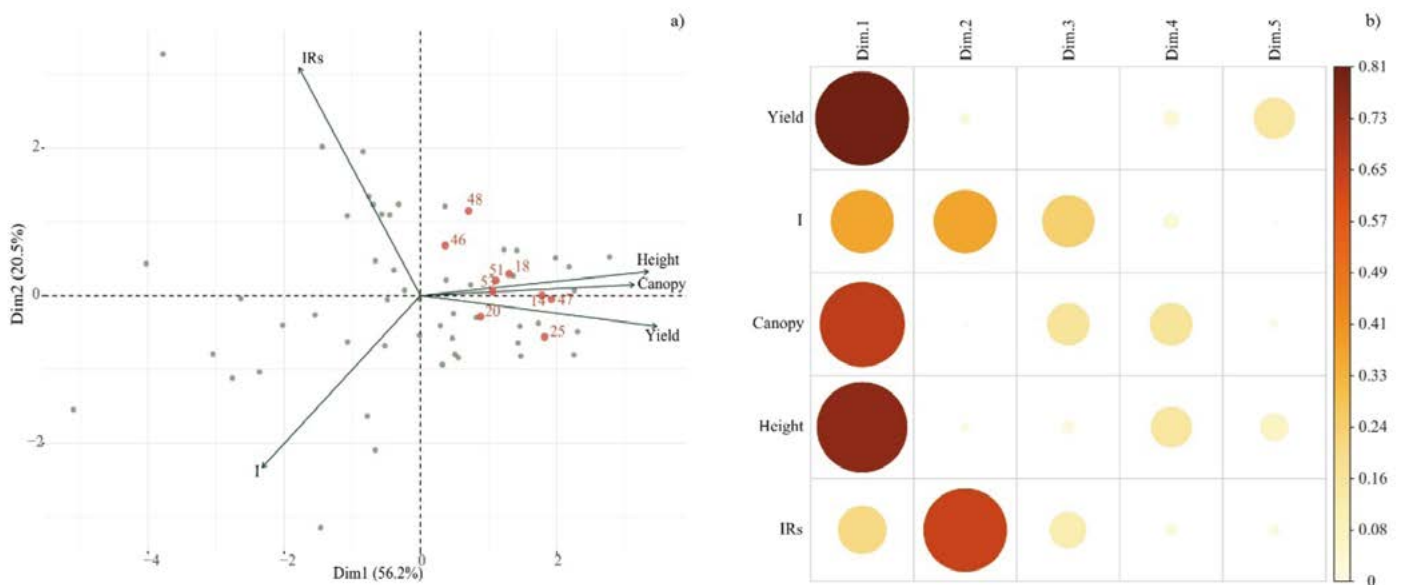


Figure 4. Representation of the population of 60 plants in the two main components. (a) Biplot graph illustrating the proximity of the nine selected plants to the morphological variables and yield. (b) Quality of representation of the variables used for selection, where circle size indicates the degree of representation in the principal components (PC). (PC1=Dim1, PC2=Dim2).

yield, plant 25 achieved the highest average (5452.6 g) over three harvest cycles. Comparing the performance of these nine plants with results from Botelho *et al.* (2010), Cardoso *et al.* (2016), and Piza *et al.* (2023), they show promising potential for further development.

CONCLUSIONS

The sequential algorithm based on conditional logic enables mass selection by ideotype in populations without replicates, addressing a methodological gap in genetic improvement programs. Its primary contribution is making scientific selection accessible in scenarios where traditional methods based on replicated designs are not feasible. As a methodology independent of numerical analysis programs, it can be implemented in Excel by plant breeders without programming expertise.

ACKNOWLEDGMENTS

This work was carried out as part of the characterization of accessions from the coffee germplasm bank at the Teocelo Experimental Site of the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias as

part of the activities on the project Conservation of Coffee Genetic Resources. We thank Enrique Hernández Reich and Jesus Pérez Parroquin, our field techs. Their support helped conserve the plantation and measure the plants.

REFERENCES

- Azimzadeh, M., Amiri, R., Davoodi-Bojd, E., Soltanian-Zadeh, H., Vahedi, S., & Hoori, M. (2010). Computer aided selection in breeding programs using genetic algorithm in MATLAB program. *Spanish Journal of Agricultural Research*, 8(3), Article 3. <https://doi.org/10.5424/sjar/2010083-1264>
- Berny Mier y Teran, J. C., Pruvot-Woehl, S., Maina, C., Barrera, S., Gimase, J. M., Banda, B., Meza, A., Kachiguma, N. A., Gichuru, E. K., Alvarado, J., Kumar, S., Alonso Castillo, J., Moreno Lopez, B., Román Ruiz, A. K., Wibowo, A., Mwatsiya, N., Devasia, J., Das, D. K., Alpizar, E., ... Montagnon, C. (2025). Global Coffea arabica variety trials reveal genotype-by-environment interactions in resistance to coffee leaf rust (*Hemileia vastatrix*). *Frontiers in Plant Science*, 16. <https://doi.org/10.3389/fpls.2025.1583595>.
- Botelho, C. E., Mendes, A. N. G., Carvalho, G. R., Bartholo, G. F., & Carvalho, S. P. (2010). Seleção de progênies F4 de cafeeiros obtidas pelo cruzamento de Icatu com Catimor. *Revista Ceres*, 57, 274-281. <https://doi.org/10.1590/S0034-737X2010000300010>.
- Breseghello, F., & Coelho, A. S. G. (2013). Traditional and Modern Plant Breeding Methods with Examples in Rice (*Oryza sativa* L.). *Journal of Agricultural and Food Chemistry*, 61(35), 8277-8286. <https://doi.org/10.1021/jf305531j>.
- Carbajal-Friedrich, A. A. J., & Burgess, A. J. (2024). The role of the ideotype in future agricultural production. *Frontiers in Plant Physiology*, 2, 1341617. <https://doi.org/10.3389/fphgy.2024.1341617>.
- Cardoso, D. A., Mendes, A. N., Carvalho, A. M., Lima, A. E., Botelho, C. E., Carvalho, G. R., & Dias, R. E. (2016). Seleção de progênies F4 oriundas do cruzamento icatu e catuaí amarelo com resistência à ferrugem. *Coffee Science - ISSN 1984-3909*, 11(4), Article 4. <http://www.coffeescience.ufla.br/index.php/Coffeescience/article/view/1183>.
- Cerón-Rojas, J. J., Gowda, M., Toledo, F., Beyene, Y., Bentley, A. R., Crespo-Herrera, L., Gardner, K., & Crossa, J. (2023). A linear profit function for economic weights of linear phenotypic selection indices in plant breeding. *Crop Science*, 63(2), 635-647. <https://doi.org/10.1002/csc2.20882>.
- Cortina, H. A., Acuña-Zornosa, J. R., Moncada Botero, M. del P., Herrera Pinilla, J. C., & Molina, D. M. (2013). Variedades de café: Desarrollo de variedades. En *Manual del cafetero colombiano: Investigación y tecnología para la sostenibilidad de la caficultura* (1a ed., Vol. 1, pp. 169–202). Cenicafé.
- Couttolenc-Brenis, E., Toral-Juárez, M. A., López Morgado, R., & Parroquin Perez, J. (2023). Respuesta a la infección de *Hemileia vastatrix* en plantas de *Coffea arabica* var. Sarchimor t5296. 1, 985-995. https://scholar.google.es/citations?view_op=view_citation&hl=es&user=ASKPqWQAAAAJ&citation_for_view=ASKPqWQAAAAJ:3fE2CSjIri8C.
- Di Rienzo, J., Casanoves, F., Balzarini, M., Gonzalez, L., Tablada, M., & Robledo, C. (2011). InfoStat (Versión 2017) [Windows 10]. Universidad Nacional de Córdoba.
- Dickmann, D. I., Gold, M. A., & Flore, J. A. (1994). The Ideotype Concept and the Genetic Improvement of Tree Crops. En *Plant Breeding Reviews* (pp. 163-193). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9780470650493.ch6>.
- Donald, C. M. (1968). The breeding of crop ideotypes. *Euphytica*, 17(3), 385-403. <https://doi.org/10.1007/BF00056241>.
- Gauffreteau, A. (2018). Using ideotypes to support selection and recommendation of varieties. *OCL*, 25(6), Article 6. <https://doi.org/10.1051/ocl/2018042>.
- Hazel, L. N. (1943). The genetic basis for constructing selection indexes. *Genetics*, 28(6), Article 6. <https://doi.org/10.1093/genetics/28.6.476>.
- Hoblyn, T. N., Grubb, N. H., Painter, A. C., & Wates, B. L. (1937). Studies in Biennial Bearing.—I. *Journal of Pomology and Horticultural Science*, 14(1), 39-76. <https://doi.org/10.1080/03683621.1937.11513464>.
- López, R., Couttolenc-Brenis, E., & Toral-Juárez, M. (2021). Rendimiento de variedades de café Coffea arabica tolerantes a *Hemileia vastatrix* causante de la roya del café. En R. Zetina Lezama, H. Tosquy Valle, A. Del Angel Pérez, A. Rios Utrera, & V. A. Esqueda Esquivel, *Ciencia y tecnología para el campo mexicano: Retos y oportunidades*. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (Vol. 1, pp. 548–558). INIFAP.
- Mendes, F. F., Ramalho, M. A. P., & Abreu, Â. de F. B. (2009). Índice de seleção para escolha de populações segregantes de feijoeiro-comum. *Pesquisa Agropecuária Brasileira*, 44, 1312–1318. <https://doi.org/10.1590/S0100-204X2009001000015>.

- Merga, D., Beksisa, L., Merga, W., & Alemayehu, D. (2023). Genetic Variability of Coffee (*Coffea arabica* L.) Germplasm in Biennial Bearing and Its Influence on Selection Efficiency. *International Journal of Agronomy*, 2023, e9995531. <https://doi.org/10.1155/2023/9995531>.
- Mishra, M. K. (2019). Genetic Resources and Breeding of Coffee (*Coffea* spp.). En J. M. Al-Khayri, S. M. Jain, & D. V. Johnson (Eds.), *Advances in Plant Breeding Strategies: Nut and Beverage Crops: Volume 4* (pp. 475-515). Springer International Publishing. https://doi.org/10.1007/978-3-030-23112-5_12.
- Moreira, P. C., de Rezende Abrahão, J. C., Porto, A. C. da M., Nadaleti, D. H. S., Gonçalves, F. M. A., Carvalho, G. R., & Botelho, C. E. (2022). Progeny Selection to Develop a Sustainable Arabica Coffee Cultivar. *Agronomy*, 12(5), 1144. <https://doi.org/10.3390/agronomy12051144>.
- Mulamba, N. N., & Mock, M. (1978). Improvement of yield potential of the ETO blanco maize (*Zea mays* L.) population by breeding for plant traits [Mexico]. *Egyptian Journal of Genetics and Cytology*, 7. <https://agris.fao.org/search/en/providers/123819/records/64735d5ce17b74d22527e90>.
- Olivoto, T., & Nardino, M. (2021). MGIDI: Toward an effective multivariate selection in biological experiments. *Bioinformatics*, 37(10), 1383-1389. <https://doi.org/10.1093/bioinformatics/btaa981>.
- Paredes-Espinosa, R., Gutiérrez-Reynoso, D. L., Atoche-Garay, D., Mansilla-Córdova, P. J., Abad-Romaní, Y., Girón-Aguilar, C., Flores-Torres, I., Montañez-Artica, A. G., Arbizu, C. I., Guerra, C. A. A., Quintana, J. L. M., Poemape, C., & Guerrero-Abad, J. C. (2023). Agro-morphological characterization and diversity analysis of *Coffea arabica* germplasm collection from INIA, Peru. *Crop Science*, 63(5), 2877-2893. <https://doi.org/10.1002/csc2.20971>.
- Pešek, J., & Baker, R. J. (1969). Desired improvement in relation to selection indices. *Canadian journal of plant science*, 49(6), 803-804. <https://cdnsiencepub.com/doi/pdf/10.4141/cjps69-137>.
- Piza, M. R., Luz, S. R. O. T. D., Andrade, V. T., Figueiredo, V. C., Abrahão, J. C. D. R., Bruzi, A. T., & Botelho, C. E. (2023). Multiple Traits Selection Strategies: A Proposal for Coffee Plant Breeding. *Agronomy*, 13(8), 2033. <https://doi.org/10.3390/agronomy13082033>.
- Rahimi, M., & Debnath, S. (2023). Estimating optimum and base selection indices in plant and animal breeding programs by development new and simple SAS and R codes. *Scientific Reports*, 13(1), 18977. <https://doi.org/10.1038/s41598-023-46368-6>.
- Resende, M. D. V. de. (2016). Software Selegen-REML/BLUP: A useful tool for plant breeding. *Crop Breeding and Applied Biotechnology*, 16, 330-339. <https://doi.org/10.1590/1984-70332016v16n4a49>.
- Rocha, J. R. do A. S. de C., Machado, J. C., & Carneiro, P. C. S. (2018). Multitrait index based on factor analysis and ideotype-design: Proposal and application on elephant grass breeding for bioenergy. *GCB Bioenergy*, 10(1), 52-60. <https://doi.org/10.1111/gcbb.12443>.
- Rodrigues, E. V., Damasceno-Silva, K. J., Rocha, M. de M., Bastos, E. A., & Teodoro, P. E. (2017). Selection of cowpea populations tolerant to water deficit by selection index 1. *Revista Ciência Agronômica*, 48, 889-896. <https://doi.org/10.5935/1806-6690.20170105>.
- Suela, M. M., Azevedo, C. F., Nascimento, A. C. C., Moura, E. T. C., Oliveira, A. C. B. de, Morota, G., & Nascimento, M. (2025). Structural Equation Modeling and Genome-Wide Selection for Multiple Traits to Enhance Arabica Coffee Breeding Programs. *Agronomy*, 15(7), Article 7. <https://doi.org/10.3390/agronomy15071686>.
- World Coffee Research. (2019). *Las variedades del café arábica (3a ed.)*. World Coffee Research.

Molecular detection of *Chlamydia* sp. in small ruminants from the central region of the state of Veracruz, Mexico

Francisco-Trinidad, Guillermo E.¹; Sánchez-Montes, Daniel, S.¹; Huerta-Peña, Javier C.¹; Lammoglia-Villagómez, Miguel A.¹; Chagoya-Fuentes, Jorge L.¹; González-Castro, Alfredo¹; Villagómez-Cortés, José A.²; Hernández-Carbajal, Gabriela R.^{1*}

¹ Universidad Veracruzana. Facultad de Ciencias Biológicas y Agropecuarias. Carretera Tuxpan Tampico Kilómetro 7.5 Universitaria C.P. 92870 Tuxpam de Rodríguez Cano, Veracruz, México.

² Universidad Veracruzana. Facultad de Medicina Veterinaria y Zootecnia. Miguel Ángel de Quevedo S/N Esq. Yáñez C.P. 91710. Veracruz, México.

* Correspondence: gabrielahernandez02@uv.mx

ABSTRACT

Objective: To identify the presence of *Chlamydia* sp. in the municipality of Coatepec, Veracruz, Mexico.

Design/methodology/approach: A total of 60 animals from five dairy goat farms were included, comprising 57 females and three males of varying ages and breed phenotypes. Samples were obtained via vaginal and preputial swabs and placed in sterile conical tubes. Endpoint PCR was performed for the detection of the *ompA VD2* gene with an amplification of 576 bp. Statistical analysis was conducted using the chi-square test for prevalence and a 2×2 contingency table for the analysis of risk factors.

Results: An overall prevalence of 5.0% was obtained from the samples collected, with three females (5.26% aged 48 months-old (6.1%), and 36 months (12.5%). A 6.8% of positive samples belonged to the Alpine and Saanen breed phenotypes; however, no risk factor attributable to the variables found was identified ($p > 0.05$).

Limitations on study/implications: The study has a small sample size and and farms number, which may limit the representativeness of the results, which may underestimate the true prevalence of the agent.

Findings/conclusions: The presence of *Chlamydia* sp. in goats in the central region of the state of Veracruz has been confirmed, highlighting the usefulness of PCR as a diagnostic tool. These results underscore the need to expand health surveillance and strengthen prevention measures in goat production systems.

Keywords: Goats, molecular diagnostics, prevalence, zoonoses.

Citation: Francisco-Trinidad, G. E., Sánchez-Montes, D. S., Huerta-Peña, J. C., Lammoglia-Villagómez, M. A., Chagoya-Fuentes, J. L., González-Castro A., Villagómez-Cortés, J. A., & Hernández-Carbajal, G. R. (2026). Molecular detection of *Chlamydia* sp. in small ruminants from the central region of the state of Veracruz, Mexico. *Agro Productividad*. <https://doi.org/10.32854/61k9nh42>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

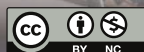
Received: November 19, 2025.

Accepted: January 29, 2026.

Published on-line: April 16, 2026.

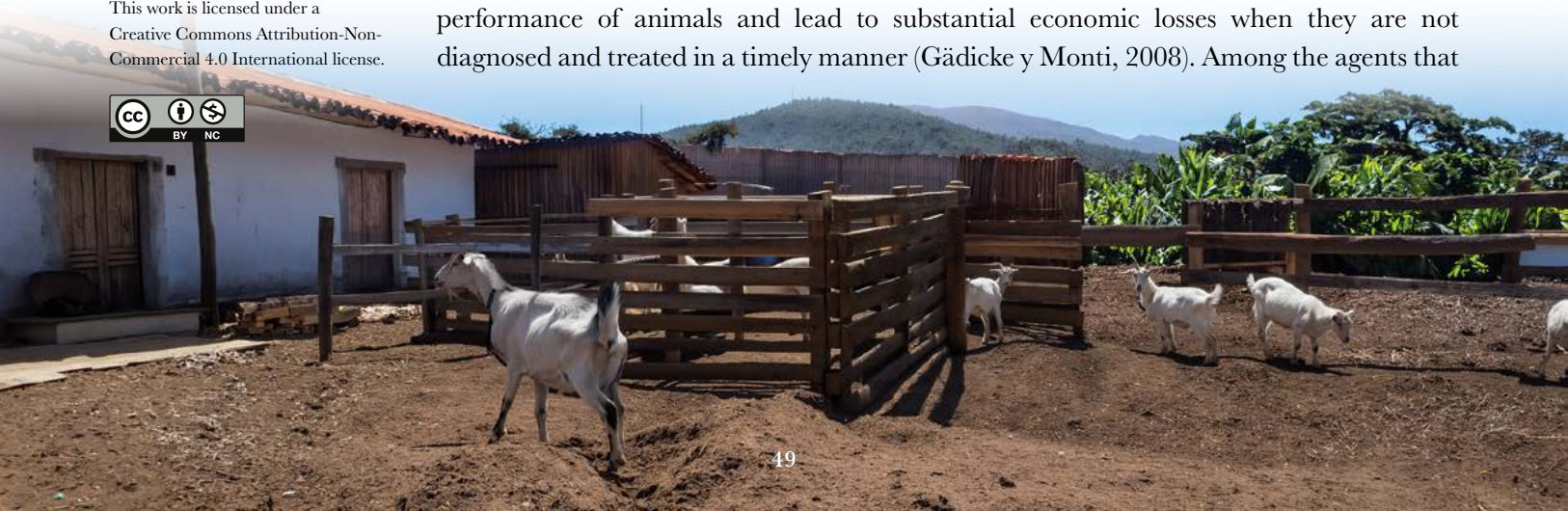
Agro Productividad, 19(2). February, 2026. pp: 49-55.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Abortions caused by bacterial diseases represent a highly significant problem in goat production and reproduction, as they have a considerable impact on the reproductive performance of animals and lead to substantial economic losses when they are not diagnosed and treated in a timely manner (Gädicke y Monti, 2008). Among the agents that



cause this type of problem is *Chlamydia* sp., recognized for its ability to cause reproductive disorders that can be confusing or even go unnoticed; furthermore, most research related to chlamydial infections has focused on sheep, which limits specific knowledge on goats. (Mora-Díaz *et al.*, 2015).

Chlamydiosis, also known as abortion in small ruminants is a highly contagious disease and is also considered a zoonosis, which poses a risk to people who are in contact with sick goats, particularly immunocompromised individuals or pregnant women (Castro-Flores *et al.*, 2021).

This disease can cause abortions, vesiculitis, epididymitis, and orchitis; however, abortions caused by chlamydiosis are more common in sheep than in goats, which makes it difficult to determine the true status of the disease (WOAH, 2018). The diagnosis of chlamydiosis is based on bacteriological isolation or the identification of nucleic acids in aborted fetuses or vaginal secretions, although its identification is often complicated due to the similarity it has with *Brucella* sp. or *Coxiella burnetii*; there is a possibility of a misdiagnosis (Esmaceli *et al.*, 2024).

In Mexico, chlamydiosis was included in group 3 of endemic diseases and exotic pests, those that must be reported monthly to veterinary authorities (DOF, 2016). In 1996, the first case of chlamydiosis in small ruminants affected by *Chlamydia psittaci* serotype 1, which is currently known as *C. abortus*, was reported in Mexico. Escalante-Ochoa *et al.* (1996) mentioned that the high incidence found led to considering *C. abortus* as playing an important role in reproductive losses in goat herds. Subsequently, microscopic lesions related to the agent were identified in fetuses aborted by goats (Escalante *et al.*, 1997).

Currently, the epidemiological situation of *Chlamydia* sp. is still limited. Studies have been conducted identifying the presence of the pathogen and finding prevalences ranging from 9.6% to 55.6% (Castro-Flores *et al.*, 2021; Sánchez-Rocha *et al.*, 2021; García-López *et al.*, 2019; Campos-Hernández *et al.*, 2014). Callejas-García (2017) found a *Chlamydia* sp. seroprevalence of 5.5%, and confirmed the presence of *C. abortus* (21.05%) in the central area of the state of Veracruz through PCR testing.

The importance of addressing chlamydiosis in the central region of Veracruz becomes particularly significant, considering that this area is a central hub for goat production. By virtue of this, it is imperative to establish constant monitoring of this pathology as a preventive measure against potential disease outbreaks. For this reason, the objective of the present research was to evaluate the presence of *Chlamydia* sp. in the municipality of Coatepec, Veracruz, Mexico using molecular techniques.

MATERIAL AND METHODS

Study Area

A cross-sectional epidemiological study was carried out, considering five goat farms located in the municipality of Coatepec, in the central area of the state of Veracruz, Mexico (19° 21' and 19° 32' north latitude, 96° 47' and 97° 06' west longitude, 500-2,900 meters above sea level) (INEGI, 2010). The goat farms specialized in milk production, with Alpine, Saanen, and crossbred phenotypes, in a semi-intensive system.

Study samples

The sample size was estimated for an expected prevalence of 50%, based on the population of the farms. The collected samples were vaginal and preputial swabs, which were transferred to sterile conical tubes, kept refrigerated, and later frozen at -20°C until processing. A total of 60 samples were collected, consisting of 57 females and three males, during April 2023.

Identification of *Chlamydia* sp. by PCR

The laboratory diagnosis was carried out using the endpoint PCR method for the identification of *Chlamydia* sp. DNA extraction was carried out using Chelex 100[®], and a 576 bp fragment of the ompA VD2 gene was amplified using the following primers: CMGP-1F: 5'-CCTTGTGATCCTTGCGCTACTTG-3'/CMGP-1R: 5'-GTGAGCAGCTCTTCGTTGAT-3', and CMGP-2F: 5'-GCCTTAAACATCTGGGATCG-3'/CMGP-2R: 5'-GCACAACCACATTCCCAT-AAAG-3' (Chahota *et al.*, 2006). The amplifications were visualized on a 2% agarose gel in 1X TAE at 85 volts for 45 min.

Statistical analysis

Statistical analysis was carried out using the Chi-square test in the mode of estimating proportions with the online program Vassarstats[®], and for the identification of risk factors with the online software Win Episcopo[®].

RESULTS AND DISCUSSION

The presence of *Chlamydia* sp. was detected by PCR, for the amplification of the fragment at 576 bp (Figure 1).

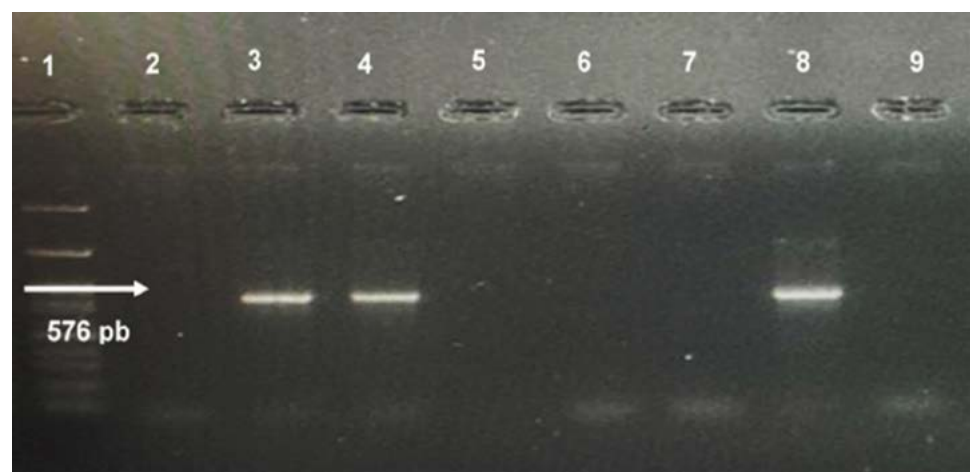


Figure 1. Electrophoretic profile of the amplification of *Chlamydia* sp. (576 bp). Lane 1: molecular weight marker (100 bp); Lane 2: Negative sample; Lane 3: Positive sample; Lane 4: Positive sample; Lane 5: Negative sample; Lane 6: Negative sample; Lane 7: Negative control, nuclease-free H₂O; Lane 8: Positive control, *Chlamydia* sp.; Lane 9: Empty lane.

The results obtained show an overall prevalence of 5.0% (95% CI: 1.7-17.7; 3/60). Out of a total of 57 females, three tested positive (5.26%; 95% CI: 1.8-14.37). Of the positive samples, in relation to age, two samples of 48 months-old (6.1%; 95% CI: 1.6-19.61) and one of 36 months-old animal (12.5%; 95% CI: 2.2-47.1) were identified. Regarding the racial type, 6.8% (95% CI: 2.3-18.2) of the positive animals belonged to Saanen and Alpine crossbreeds. No pregnant or lactating females were identified among the positive animals.

The statistical analysis did not show a significant association between the variables evaluated, so no risk factors were identified ($p > 0.05$) (Table 1). These results identify the presence of *Chlamydia* sp. in the municipality of Coatepec, Veracruz; however, this area is where nearly 90% of the goat inventory in Veracruz is concentrated (Román-Ramírez *et al.*, 2017). Previous studies conducted in Mexico reported prevalences of 9.6% to 55.6% in areas such as Guanajuato, Morelos, Coahuila, Querétaro, Puebla, and Veracruz (Castro-Flores *et al.*, 2021; Sánchez-Rocha *et al.*, 2021; García López *et al.*, 2019). However, Callejas-García (2017), in his research in the central area of the state of Veracruz, reported a seroprevalence of 5.9%, finding that the municipalities of Perote and Villa Aldama were risk factors ($P < 0.05$) and that no positive cases were identified in the municipality of Coatepec. However, in the present study, positive animals were indeed found.

The environmental conditions in this mountainous region are usually favorable for *Chlamydia* sp., as temperatures range from 12 to 25 °C. This results in the pathogen being released into the environment through fluids or excretions, allowing the microorganism to survive for several weeks in cold and humid conditions. On top of that, the lack of strategies on farms to separate females nearing parturition and newly kidding goats promotes easier infection, since during birth and abortions a large load of *Chlamydia* bacteria is released, contaminating the feed, water, and bedding, and favoring the transmission and persistence of the agent in affected herds (Rodolakis y Laroucau, 2015; Talafha *et al.*, 2012).

Table 1. Prevalence and risk factors associated with the presence of *Chlamydia* sp. in the central area of the state of Veracruz, Mexico.

Variable	n	+	Prevalence (%)	95% CI	OR*	95% CI	P
Sex							
Female	57	3	5.3	1.8-14.4	-	-	-
Male	3	0	-	-	-	-	-
Age, months*old							
60	2	0	-	-	-	-	-
48	33	2	6.1	1.6-19.6	1.0	-	-
36*	8	1	12.5	2.2-47.1	2.2	0.17-27.98	0.49
24	3	0	-	-	-	-	-
12	14	0	-	-	-	-	-
Breed phenotype							
Alpine	11	0	-	-	-	-	-
Saanen	5	0	-	-	-	-	-
Crosses	44	3	6.8	2.3-18.2	-	-	-

* OR (Odds Ratio) should be interpreted with caution due to the small sample size.

Certainly, the presence of *Chlamydia* sp. in flocks of small ruminants depends on various factors such as geographic location, the breed, age, sex, and number of parturitions, as well as the type of management, hygiene and preventive medicine practices, and the movement of animals (Afrisham *et al.*, 2023). In the present study, the animals that tested positive were females aged 36 to 48 months-old, but abortions were rare, according to the information provided by farmers.

Castro-Flores *et al.* (2021) mentioned that females are usually affected by chlamydiosis at a young age and with a lower number of parturitions; these authors also pointed out that the interval between abortion, kids birth, and sample collection is of utmost importance to ensure a timely diagnosis; in addition, Palomares-Reséndiz *et al.* (2020) reported that goats between 37 and 48 months-old show a higher frequency of positive cases of chlamydiosis. In this regard, it can be considered that the timing of sampling and the low frequency of abortions may influence the detection of the agent, independently of the reproductive signs of disease on the evaluated farms. Although the bacteriological isolation of *Chlamydia* sp. is still considered the reference method for identification (WOAH, 2018), molecular PCR techniques are considered the ideal tests to confirm the agent in clinical cases suspected of chlamydiosis, as well as for epidemiological surveillance. Official organizations consider molecular tests as complementary diagnostic tests, which must be corroborated by pathological analysis to confirm the diagnosis; however, microbiological diagnosis can fail due to the loss of bacterial viability, so techniques like PCR can detect the agent even when the reference method is not viable (Esmaceli *et al.*, 2024; Castro-Flores *et al.*, 2021).

In Mexico, Sánchez-Rocha *et al.* (2021) identified the presence of *C. abortus* in goats that had experienced abortions; these authors reported 9.6% positives with samples of vaginal exudates in the states of Coahuila, Jalisco, Querétaro, and Veracruz; in this last state, they only found two positive samples, which is similar to what was identified in the present study.

Rodolakis and Laroucau (2015) mentioned that the ideal samples for PCR analysis are aborted fetuses and placentas, due to their high bacterial load, although it is also possible to demonstrate their presence in vaginal exudates, which can be effectively used for the diagnosis of chlamydiosis in small ruminants (Mora-Díaz *et al.*, 2015; Campos-Hernández *et al.*, 2014).

Likewise, the introduction of animals without a prior diagnosis represents a significant risk factor for the spread of the agent, particularly due to the absence of a standardized reference test, which hinders the timely detection of the agent, since it is considered a rare or exotic disease (Palomares-Reséndiz *et al.*, 2020).

The results of the present study confirm the presence of *Chlamydia* sp. in the central area of the state of Veracruz, although there is a previous study in 14 municipalities of the central area of Veracruz, where the presence of *Chlamydia* sp. was reported by PCR, but the municipality of Coatepec was found to be negative (Callejas-García, 2017), which suggests that the agent is circulating in the area and highlights the need to strengthen epidemiological surveillance in the contiguous urban areas.

CONCLUSIONS

The present study confirms the presence of *Chlamydia* sp. in the municipality of Coatepec, in the central region of the state of Veracruz in female goats. Although it was not possible to identify the species circulating in the region, the results found, coupled with literature available in the central area of Veracruz, confirm and provide evidence of the circulation of the agent in mature animals. Likewise, the need for monitoring the different reproductive stages of females is highlighted. These results underscore the need to implement preventive measures and epidemiological surveillance to mitigate the impact of *Chlamydia* sp. in the region.

ACKNOWLEDGMENTS

Thanks are extended to the Caprine Species System of the state of Veracruz (SIPE-CAV A.C.) and to its late President, Lic. Ignacio Cambabia-González, for the facilities provided for sampling animals in their farms. Likewise, we thank the Center for Tropical Medicine (CMT-UNAM) for the support provided for laboratory diagnosis.

REFERENCES

- Afrisham, S., Golchin, M., Mohammadi, E., Eskandarzade, N., & Shamshirgaran, M.A. (2023). Prevalence of *Chlamydia abortus* infection in aborted sheep and goats in Kerman Province, Southeast of Iran. *Iranian Journal of Veterinary Science and Technology*, 15(3): 42-47. <https://doi.org/10.22067/ijvst.2023.82794.1263>
- Callejas-García S.A. (2017). Estudio epidemiológico de la clamidiasis caprina en la zona centro del estado de Veracruz [Tesis de maestría]. Ciudad de México: Universidad Nacional Autónoma de México.
- Campos-Hernández, E., Vázquez-Chagoyán, J.C., Salem, A.Z.M., Saltijeral-Oaxaca, J.A., Escalante-Ochoa, C., López-Heydec, S.M., & Montes de Oca-Jiménez, R. (2014). Prevalence and molecular identification of *Chlamydia abortus* in commercial dairy goat farms in a hot region in Mexico. *Tropical Animal Health and Production*, 46: 919-624. <http://dx.doi.org/10.1007/s11250-014-0585-6>
- Castro-Flores, R., Gaxiola, S.M., Díaz-Aparicio, E., Limón-González, M.M., Romero-Jaramillo, A., Enríquez-Verdugo, I., Castro, N., Rodríguez-Gaxiola, M.A., Montero-Pardo, A., & Díaz, D. (2021). Prevalencia de *Chlamydia abortus* en cabras con problemas de aborto en la zona centro de Sinaloa, México. *Biocencia*. 23(3):142-150. <https://doi.org/10.18633/biocencia.v23i3.1290>
- Chahota R, Ogawa H, Mitsuhashi Y, Ohya K, Yamaguchi T, & Fukushi H. (2006). Genetic diversity and epizootiology of *Chlamydophila psittaci* prevalent among the captive and feral avian species based on VD2 region of ompA gene. *Microbiology and Immunology*; 50(9):663-78. <https://dx.doi.org/10.1111/j.1348-0421.2006.tb03839.x>
- Escalante-Ochoa, C., Díaz-Aparicio, E., Segundo-Zaragoza, C., & Suárez-Güemes, F. (1997). Isolation of *Chlamydia psittaci* involved in abortion of goats in Mexico: first report. *Revista Latinoamericana de Microbiología*, 39:117-121.
- Escalante-Ochoa, C., Rivera-Flores, A., Trigo-Tavera, F., & Romero-Martínez, J. (1996). Detection of *Chlamydia psittaci* enteric subclinical infections in adult sheep, through cell culture isolation. *Revista Latinoamericana de Microbiología*, 38:17-23.
- Esmaceli, H., Hamedi, M., Madani, S.A., & Barin, A. (2024). Diagnosis of *Chlamydia abortus* by Isolation in cell culture and real time PCR in aborted sheep and goats. *Journal of Medical Bacteriology*, 12(4): 9-16. <https://doi.org/10.18502/jmb.v12i4.17003>
- Gädicke, P., & Monti, G. (2008). Aspectos epidemiológicos y de análisis del síndrome de aborto bovino. *Archivos de Medicina Veterinaria*, 40(3): 223-234. <https://dx.doi.org/10.4067/S0301-732X2008000300002>
- García-López, X., Herrera-López, E., Rico-Chávez, O., Tortora-Pérez, J., Díaz-Aparicio, E., Palomares-Resendiz, E.G., & Gutiérrez-Hernández, J.L. (2019). Prevalencia de *Chlamydia abortus* en rebaños caprinos de Guanajuato, México. *Revista Académica Ciencia Animal*, 17(supl. 1):484-487.
- INEGI. Instituto Nacional de Estadística y Geografía. (2010). Datos geográficos del municipio de Coatepec, Veracruz. Aguascalientes, México: Instituto Nacional de Estadística y Geografía. Retrieved from: https://www.inegi.org.mx/contenidos/app/mexicocifras/datos_geograficos/30/30038.pdf

- Mora-Díaz, J.C., Díaz-Aparicio, E., Herrera-López, E., Suárez-Güemes, F., Escalante-Ochoa, C., Jaimes-Villareal, S., & Arellano-Reynoso, B. (2015). Isolation of *Chlamydia abortus* in dairy goat herds and its relation to abortion in Guanajuato, Mexico. *Veterinaria Mexico OA*, 2(1):1-10. <http://dx.doi.org/10.21753/vmoa.2.1.339>
- Palomares-Reséndiz, E.G., Mejía-Sánchez, P., Aguila-Romero, F., De la Cruz-Colin, L., Jiménez-Severiano, H., Leyva-Corona, J.C., Morales-Pablos, M.I., & Díaz-Aparicio, E. (2020). Frecuencia y factores de riesgo asociados a la presencia de *Chlamydia abortus*, en rebaños ovinos en México. *Revista Mexicana de Ciencias Pecuarias*, 11(3):783-794. <https://doi.org/10.22319/rmcp.v11i3.5269>
- Rodolakis, A., & Laroucau, K. (2015). Chlamydiaceae and chlamydial infections in sheep or goats. *Veterinary Microbiology*, 181(1-2):107-118. <https://doi.org/10.1016/j.vetmic.2015.07.010>
- Román-Ramírez, D.L., Martínez-Herrera, D. I., Villagómez-Cortés, J.A., Peniche-Cardena, A.E.J., Morales-Álvarez, J.F., & Flores-Castro, R. (2017). Epidemiología de la brucelosis caprina en la Zona Centro del Estado de Veracruz. *Gaceta Médica de México*, 153:26-30.
- SAGARPA (2016). Acuerdo mediante el cual se dan a conocer en los Estados Unidos Mexicanos las enfermedades y plagas exóticas y endémicas de notificación obligatoria de los animales terrestres y acuáticos. Publicado en el Diario Oficial de la Federación el jueves 29 de noviembre de 2018. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. México. http://www.dof.gob.mx/nota_detalle.php?codigo=5436016&fecha=04/05/2016
- Sánchez-Rocha, L., Arellano-Reynoso, B., Hernández-Castro R., Palomares-Resendiz, G., Barradas-Piña, F., & Díaz-Aparicio, E. (2021). Presence of *Chlamydia abortus* in goats with a history of abortions in Mexico. *Abanico Veterinario*, 11:1-14. <http://dx.doi.org/10.21929/abavet2021.26>
- Talafha, A., Mohammed, M., Mustafa, M., & Ahmad, M. (2012). Prevalence and risk factor associated with *Chlamydophila abortus* infection in dairy herds in Jordan. *Tropical Animal Health and Production*, 44(8):1841-1846. <https://doi.org/10.1007/s11250-012-0146-9>
- World Organisation for Animal Health (WOAH). (2019). Manual of diagnostic tests and vaccines for terrestrial animals. Paris: World Organisation for Animal Health. Retrieved from: <https://www.woah.org/en/what-we-do/standards/codes-and-manuals/>

Productivity of maize genotypes in acid soils of southern Veracruz with and without dolomite

Vázquez-Hernández, Marcos V.¹; Tosquy-Valle, Oscar H.¹; Zetina-Lezama, R.¹; Barrón-Freyre, Sabel²; Fadda Lucas A.^{1*}

¹ Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro de Investigación Regional Golfo Centro. Campo Experimental Cotaxtla. Medellín de Bravo, Veracruz, México. C. P. 94270.

² Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro de Investigación Regional Golfo Centro. Campo Experimental Huimanguillo. Huimanguillo, Tabasco, México. C.P. 96999.

* Correspondence: fadda.lucas@inifap.gob.mx

ABSTRACT

Objective: To determine the effect of soil acidity on the growth and yield of maize genotypes (*Zea mays* L.) under rainfed production conditions, and identify those with greater productive efficiency with and without the application of dolomitic lime.

Design/methodology/approach: Twelve maize genotypes were evaluated in an acidic soil using a randomized complete block design with four replications. Two trials were established: one with dolomitic lime application and one without liming. Plant height, main ear insertion height, and grain yield were recorded. Data were analyzed through individual analyses of variance, mean comparison tests (LSD, $\alpha=0.05$), and correlation analysis. Productive efficiency under limed and non-limed conditions was estimated using the geometric mean index (*GMI*) and the relative efficiency index (*REI*).

Results: Soil acidity reduced plant height by an average of 7.8%, ear height by 14.4%, and grain yield by 32.9%. SINT 1A and SINT 2B × V540 showed the best adaptation under acidic soil conditions. These same genotypes also exhibited the highest (*GMI*) and (*REI*) values, indicating the greatest productive efficiency both with and without dolomitic lime application. Under limed soil conditions, V537C × V540 was the most productive genotype, followed by SINT 2B × V540 with acceptable grain yield.

Limitations on study/implications: The evaluation of genotypes was conducted under conditions of soil acidity combined with drought stress, which allowed the identification of genotypes with greater productive efficiency under adverse edaphoclimatic conditions. Multi-environment evaluations and additional cropping cycles are recommended to confirm yield stability.

Findings/conclusions: Soil acidity strongly affected plant architecture and productivity; however, liming improved plant growth and grain yield. SINT 3B × V-540 stood out for its stability and yield, making it a promising option for acidic soils in the Mexican tropics.

Keywords: *Zea mays* L., liming, yield stability, acid tolerance, genotype × environment interaction.

Citation: Vázquez-Hernández, M. V., Tosquy-Valle, O. H., Zetina-Lezama, R., Barrón-Freyre, I., & Fadda-Lucas, A. (2026). Productivity of maize genotypes in acid soils of southern Veracruz with and without dolomite. *Agro Productividad*. <https://doi.org/10.32854/vkkmzn97>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: November 9, 2025.

Accepted: January 7, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 57-66.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

In southeastern Mexico, particularly in the tropical and subtropical regions of Veracruz, Chiapas, and Oaxaca, maize (*Zea mays* L.) production is carried out mainly under rainfed conditions and with residual soil moisture. These environments have high productive



potential; however, they also present edaphic and climatic constraints that limit grain yield. Among the most important limiting factors is soil acidity, a common characteristic of soils formed under high rainfall conditions (García, 1973). In southern Veracruz, these conditions are widespread, as extensive areas exhibit soil pH values below 5.0, which reduces phosphorus availability, promotes the leaching of base cations (Ca, Mg, and K), and increases the presence of exchangeable aluminum. This, in turn, restricts root growth and nutrient uptake (Zetina-Lezama *et al.*, 2002; Zetina-Lezama *et al.*, 2005). In maize, this type of edaphic stress is associated with reduced vegetative growth, decreases in plant height and ear insertion height, phenological delays, and yield losses that may exceed 70%, depending on the genetic tolerance of the crop and the severity of soil acidity (Dewi-Hayati *et al.*, 2014).

In this scenario, nutrient management is a determining factor. The application of dolomitic lime is a widely used practice to increase soil pH, reduce aluminum toxicity, and improve nutrient availability in the surface horizon (The *et al.*, 2010). Studies conducted in tropical soils have reported significant increases in root development, plant vigor, and yield following dolomite application (Ramírez-Sánchez *et al.*, 2020). However, in rainfed and low-input production systems, this practice is not always feasible for farmers due to the high costs associated with transport and application, as well as the limited capacity to maintain pH correction over the long term (Zetina-Lezama *et al.*, 2005).

Additionally, drought occurrence is common in southern Veracruz under both rainfed and residual moisture conditions, and depending on its intensity and duration, it can significantly affect maize productivity (Zetina-Lezama *et al.*, 2005). A key strategy to increase crop yields under the aforementioned edaphoclimatic conditions is the use of genetic materials adapted to acidic soils and tolerant to drought (Graham, 1984; Sierra *et al.*, 2019; Tandzi *et al.*, 2018).

Within the maize breeding program of the Cotaxtla Experimental Station of the National Institute for Forestry, Agriculture and Livestock Research (INIFAP), hybrids, synthetic varieties, and improved varieties are available that have shown good adaptability in tropical and subtropical areas of southeastern Mexico. In this context, the objectives of the present study were: (1) to determine the agronomic and productive response of 12 maize genotypes (*Zea mays* L.) developed by INIFAP under rainfed conditions, with and without dolomitic lime application, in an acidic soil of southern Veracruz; and (2) to identify materials with better adaptation and productive efficiency under acidic soil conditions.

MATERIALS AND METHODS

Study area

To evaluate the maize genotypes, two field experiments were established during the 2024 summer-autumn growing season in an agricultural field located in the municipality of Juan Rodríguez Clara, Veracruz, Mexico (18° 01' N, 95° 23' W; 128 m above sea level), under rainfed conditions. The site is characterized by a warm subhumid climate (Aw_0), with a mean annual precipitation of 1462 mm (García, 1973). The predominant

soils are dystrophic Cambisols with a sandy loam texture, characterized by low phosphorus availability and the presence of and interchangeable bases (Zetina-Lezama *et al.*, 2002; 2005).

Liming rate and soil pH determination

Prior to the establishment of the experiment, soil samples were collected from the 0-20 cm layer, and an initial soil pH of 4.6 was determined, indicating a restrictive edaphic condition associated with low fertility. These soil characteristics justified the application of dolomitic lime to improve crop productivity. The liming treatment aimed to increase the original soil pH to approximately 5.4. In the soil where one of the experiments was established, dolomitic lime was applied at a rate of 2.25 t ha⁻¹. This rate was estimated using the equation: $Y = 11.708 - 1.954x$, developed by INIFAP for acidic soils (Zetina *et al.*, 2002); where x corresponds to the dolomitic lime requirement and Y corresponds to the dolomitic lime requirement (t ha⁻¹) needed to reach a soil pH ≥ 5.4 , which is considered optimal for maize development (Ruíz *et al.*, 2013). Dolomitic lime was broadcast-applied 15 days prior to sowing and incorporated into the soil with a single disk harrow pass to an approximate depth of 20 cm (Zetina *et al.*, 2017). The second experiment, established in the same soil, was conducted under natural acidic soil conditions, without liming application.

For soil pH determination, composite soil samples were collected in each experiment, consisting of three subsamples per replication, at three stages of the crop cycle: 15 days before sowing (prior to liming), 25 days after sowing, and at physiological maturity. In all samples, soil pH was measured in water using a 1:2 soil-solution ratio with a Hanna potentiometer (model HI9812-51). The values obtained for each replication were averaged to calculate the mean soil pH for each sampling period (Zetina *et al.*, 2017).

Genetic materials

In both experiments, 12 maize genotypes from the INIFAP maize breeding program at the Campo Experimental Cotaxtla were evaluated: H-518, H-520, SINT 1A, SINT 2B, SINT 4B, V-537C, V-540, and five intervarietal crosses derived from materials adapted to the humid tropics: SINT 2B \times V-540, SINT 3B \times V-540, SINT 4B \times V-540, SINT 5B \times V-540, and V-537C \times V-540 (Sierra *et al.*, 2019).

Experimental design and agronomic management

The experiments were established at a planting density of 62,500 plants ha⁻¹, using a randomized complete block design with four replications. Experimental plots consisted of four rows, each 5 m in length, spaced 0.80 m apart, with the two central rows considered as the effective plot area.

Crop establishment practices, fertilization, weed control, and phytosanitary management were carried out in accordance with INIFAP recommendations for maize production in tropical regions (Palafox *et al.*, 2010).

Explanatory and response variables

During the crop cycle, rainfall at the experimental site was recorded using a plastic rain gauge with a 40-mm capacity and counting ring. Plant height and main ear insertion height were measured in centimeters at the end of the growing cycle. Grain yield was estimated based on the weight of ears harvested from the effective plot, which were shelled and adjusted to a 14% moisture content.

Statistical analysis

Analyses of variance were performed separately for each experiment (with and without dolomitic lime). Mean comparisons were conducted using the Least Significant Difference test (LSD, $\alpha=0.05$). In addition, correlation coefficients between the quantified variables and grain yield were calculated following the procedure described by Olivares (1994).

The yield efficiency of the genotypes under limed and non-limed conditions was estimated using the geometric mean (MG_I):

$$MG_I = (Y_{ii} \times Y_{ci})^{1/2}$$

where: Y_{ii} and Y_{ci} correspond to the grain yield of genotype i under non-limed and limed conditions, respectively.

Similarly, yield efficiency was also estimated using the relative efficiency index (IER_I)

$$IER_I = \left(\frac{Y_{ii}}{Y_i} \right) \left(\frac{Y_{ci}}{Y_c} \right)$$

where: Y_{ii} and Y_{ci} represent the overall mean grain yield under non-limed and limed conditions, respectively, according to Graham (1984) and Tandzi *et al.* (2018).

Higher values of MG_I and IER_I indicate greater productive efficiency and superior genotype performance across both evaluation environments.

RESULTS AND DISCUSSION

Rainfall and soil pH dynamics during the crop cycle

Although total accumulated rainfall during the crop cycle reached 772 mm (310 mm from sowing to flowering and 462 mm from flowering to crop maturity), a level close to that considered optimal for adequate maize development (Kranz *et al.*, 2008), its distribution was irregular in both timing and amount. Periods of drought occurred during the cycle and affected the yield of the genotypes in both experiments. Consequently, the results of this study reflect the combined effect of soil management conditions (with and without liming) and drought occurrence, which is common in this maize-producing region.

Regarding soil pH, the incorporation of dolomitic lime increased the initial value from 4.9 to 5.4 by the end of the crop cycle, evidencing the positive effect of liming on the

neutralization of soil acidity. However, the temporal dynamics of soil pH showed a more pronounced increase during the vegetative development of maize (pH 6.6), whereas under non-limed conditions, soil pH values remained relatively stable throughout the crop cycle (Figure 1).

Response of plant height and ear insertion to liming in acidic soil

Genotypes that showed greater stability in plant height also tended to maintain a more uniform ear insertion across environments. Under dolomitic lime application (CD), significant differences among genotypes were observed for both plant height and ear insertion height (Table 1). The highest values for both traits were recorded in genotypes such as V-537C × V-540, SINT 4B × V-540, and SINT 3B × V-540, which were consistently grouped in the upper statistical category, indicating a positive response to liming and a greater capacity to take advantage of the chemical correction of acidic soil.

Under non-limed conditions (SD), V-540 stood out compared to the other genotypes, followed by SINT 2B × V-540 and SINT 5B × V-540, which maintained relatively high values for both plant height and ear insertion height. These genotypes showed a lower relative reduction under uncorrected soil acidity.

The analysis of percentage reduction between environments with and without dolomite allowed the identification of consistent patterns of stability and sensitivity. V-540, SINT 2B × V-540, and SINT 5B × V-540 exhibited the lowest reductions in both traits ($\leq 6\%$), standing out as the most stable genotypes under soil acidity conditions. In contrast, materials such as SINT 3B × V-540, SINT 4B × V-540, and V-537C × V-540 showed parallel and pronounced reductions, particularly in ear insertion height, indicating a greater dependence on liming to express their morpho-agronomic potential.

Overall, the coordinated response of plant height and ear insertion height reflects the close link between vegetative vigor and reproductive development in maize grown under acidic soil conditions. The contrasting stability patterns among genotypes suggest

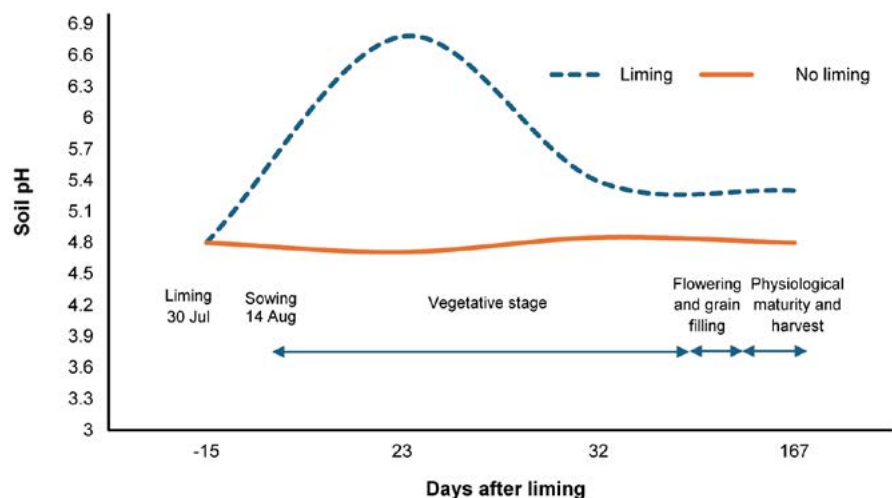


Figure 1. Soil pH dynamics in a dystrophic Cambisol under limed and non-limed conditions during the maize cropping cycle in Juan Rodríguez Clara, Veracruz.

Table 1. Effect of acidic soil stress on plant height and ear insertion height of maize genotypes evaluated under conditions with and without dolomitic lime application. Juan Rodríguez Clara, Veracruz, Mexico. Summer-autumn growing season, 2024.

Genotype	AP (cm)		AP Reduction (%)	AM (cm)		AM Reduction (%)
	CD	SD		CD	SD	
H-518	149.80cde	143.00ab	4.53	71.50de	59.43ef	16.90
H-520	146.45e	148.58ab	1.48	69.08e	63.50def	8.08
SINT 1A	153.33b-e	139.70bc	8.91	84.00ab	67.35cde	19.84
SINT 2B	156.98a-e	146.83ab	6.48	79.20a-d	66.08def	16.53
SINT 2B × V-540	162.08a-e	152.50ab	5.91	80.15a-d	74.93abc	6.55
SINT 3B × V-540	166.13abc	147.50ab	11.21	87.83a	67.85cde	22.77
SINT 4B	147.30de	126.75c	13.95	72.43cde	58.68f	18.99
SINT 4B × V-540	167.83ab	147.68ab	11.99	81.93abc	65.75def	19.74
SINT 5B × V-540	159.58a-e	150.00ab	6.01	76.95b-e	76.58ab	0.43
V-537C	161.20a-e	148.40ab	7.93	81.63abc	67.28cde	17.61
V-537C × V-540	172.38a	149.68ab	13.17	86.93a	70.25bcd	19.21
V-540	164.33a-d	155.33a	5.48	85.58ab	80.03a	6.52
Mean	158.95	146.33	7.84	79.76	68.14	14.43
DMS (0.05)	17.669	13.133		9.7643	8.4775	
Correlation with yield	0.247 ns	0.284 ns		0.334 ns	0.214 ns	

AP=Plant height. AM=Ear insertion height. With dolomitic lime application (CD). Without dolomitic lime application (SD). Correlation coefficient with grain yield. Different letters within columns indicate significant differences (LSD=0.05).

differences in physiological efficiency to sustain growth under edaphic stress, likely associated with tolerance to Al^{3+} toxicity and with Ca and Mg availability. In this context, both traits emerge as early and reliable indicators of genotypic adaptation to soil acidity (Kochian *et al.*, 2015).

Effect of liming on grain yield in maize genotypes

Regarding grain yield, the analysis of variance revealed a strong response to liming, with significant differences among genotypes both in achieved yield levels and in the magnitude of yield reduction under uncorrected soil acidity. Some materials maintained relatively high yields across both environments, whereas others relied heavily on dolomitic lime application to fully express their productive potential (Table 2), confirming the existence of genetic variability in the response to soil acidity and its correction through liming.

Under non-limed conditions, higher coefficients of variation and larger error mean squares were observed, reflecting greater yield instability associated with Al^{3+} toxicity stress and reduced availability of basic cations. This response pattern has been widely documented in maize cultivated on acidic soils (von Uexküll & Mutert, 1995; The *et al.*, 2010; Lestari, 2016; Chairiyah, 2020).

With dolomitic lime application, grain yields ranged approximately from 2,400 to 3,700 kg ha⁻¹ (Table 3). The highest values were recorded for V-537C × V-540, SINT

Table 2. Mean squares and statistical significance of the variables measured in maize trials conducted on acidic soil, with and without dolomitic lime application.

SV	df	AP	AM	Grain yield
Dolomitic lime application (CD)				
Treatments	11	278.48 ns	153.05**	576977.33**
Blocks	3	969.93	423.55	64820.29
Error	33	150.84	46.07	65115.248
Total	47			
CV (%)		7.73	8.51	8.86
No dolomitic lime application (SD)				
Treatments	11	216.29**	167.78**	298013.51**
Blocks	3	743.38	295.18	226268.7
Error	33	83.33	34.73	87094.97
Total	47			
CV (%)		6.24	8.65	15.48

SV=source of variation. df=degrees of freedom. AP=plant height. AM=ear insertion height. CV=coefficient of variation. ** significant at 0.01. * significant at 0.05. ns=not significant.

Table 3. Mean grain yield of maize genotypes evaluated under acidic soil conditions, with and without dolomitic lime application, and estimated selection indices.

Genotype	Grain yield (kg ha ⁻¹) with dolomite	Grain yield (kg ha ⁻¹) without dolomite	MGi	IERi
H-518	2645.70def	1646.90cd	2087.39	0.794
H-520	2386.00f	1900.90a-d	2129.68	0.826
SINT 1A	3084.20bc	2320.30a	2675.09	1.303
SINT 2B	2935.50bcd	1550.90d	2133.7	0.829
SINT 2B × V-540	3141.20b	2316.70a	2697.6	1.325
SINT 3B × V-540	3008.50bcd	2226.30ab	2587.95	1.22
SINT 4B	3147.00b	1560.00d	2215.73	0.894
SINT 4B × V-540	2403.00f	2064.70abc	2227.45	0.904
SINT 5B × V-540	2808.30b-e	1780.10cd	2235.83	0.911
V-537C	2509.50ef	1795.70cd	2122.76	0.821
V-537C × V-540	3719.90a	1909.50a-d	2665.12	1.294
V-540	2772.60cde	1803.40bcd	2236.11	0.911
Mean	2880.12	1906.28	2334.53	1.003

Genotypes with different letters within each grain yield column are statistically different (LSD=0.05).

4B, and SINT 2B × V-540, which consistently ranked within the upper statistical group, indicating a strong responsiveness to the partial neutralization of soil acidity. In contrast, under non-limed conditions, yields declined across genotypes, ranging from approximately 1,500 to 2,300 kg ha⁻¹, a reduction that was also influenced by the occurrence of terminal drought. Nevertheless, SINT 2B × V-540, SINT 1A, and SINT 3B × V-540 maintained comparatively higher yields under uncorrected acidic soil conditions.

The average yield reduction between environments was close to 33%, although marked contrasts among genotypes were observed. SINT 4B × V-540 exhibited a moderate reduction ($\approx 14\%$), standing out as the most stable material, whereas V-540 showed an intermediate reduction. In contrast, SINT 4B, H-518, H-520, V-537C × V-540, and SINT 2B showed the greatest yield losses, highlighting their strong dependence on liming to express their productive potential. This pattern is consistent with reports for maize cultivated on acidic soils, where yield losses associated with Al^{3+} toxicity typically range between 20 and 50% (The *et al.*, 2010; Lestari, 2016).

The results confirm that liming significantly increases grain yield in acidic soils (Chairiyah *et al.*, 2020); however, the magnitude of the response depends on the degree of genetic adaptation of each material. The coexistence of genotypes that are stable under uncorrected soil acidity and others that respond strongly to pH correction underscores the need to implement selection strategies tailored to specific edaphic conditions and, where appropriate, to assess the feasibility of using soil amendments in production systems to improve productivity (Ramírez-Sánchez *et al.*, 2020).

Productive efficiency of genotypes under contrasting soil acidity conditions

The geometric mean allowed the identification of genotypes with greater yield stability across contrasting environments, by penalizing those materials that exhibit high performance under favorable conditions but suffer sharp yield reductions under stress. Genotypes SINT 2B × V-540, SINT 1A, and SINT 3B × V-540 stood out by presenting geometric mean values above the overall average, indicating better adaptation under both limed and uncorrected acidic soil conditions. This response is particularly desirable for the selection of materials intended for regions with persistent soil acidity. In contrast, genotypes such as H-518 and SINT 4B showed low geometric mean values, reflecting greater susceptibility to edaphic stress.

The relative efficiency index complemented the stability analysis by integrating the relative performance of genotypes across both environments. Values of greater than 1 indicated productive performance above the general mean. In this context, SINT 2B × V-540, SINT 1A, and V-537C × V-540 exhibited the highest values, reflecting a favorable combination of high yield and stability under soil acidity conditions. Conversely, H-518 and SINT 4B recorded index values below unity, confirming their limited performance in edaphically restrictive environments.

The geometric mean and the relative efficiency index consistently discriminated genotypes with stable performance under edaphic stress. The agreement between both indicators confirmed the identification of materials capable of maintaining grain yield under acidic soil conditions, which is consistent with previous reports highlighting the combined use of stability and efficiency metrics for selecting maize genotypes in soils with chemical limitations (Ochoa-Cadavid *et al.*, 2019; Tirado-Soto *et al.*, 2019).

Relationship between plant architecture and grain yield under soil acidity

Correlation analysis between plant height, ear insertion height, and grain yield showed low and non-significant associations under both soil conditions (Table 1). This indicates

that, although soil acidity affects plant architecture, these variations do not necessarily translate proportionally into differences in grain yield. The low magnitude of the correlations suggests that yield performance under acidic stress is governed by a more complex set of physiological traits, likely associated with aluminum tolerance, nutrient use efficiency, and stability of grain filling (Kochian *et al.*, 2015).

CONCLUSIONS

Soil acidity significantly reduced plant height, ear insertion height, and grain yield in most of the evaluated genotypes, confirming the high sensitivity of maize to aluminum toxicity and low availability of phosphorus and exchangeable bases under acidic soil conditions.

Within the evaluated set, the genotypes SINT 2B × V-540, SINT 1A, V-537C × V-540, and SINT 3B × V-540 exhibited favorable performance in terms of productivity and stability under contrasting acidity conditions, positioning them as promising alternatives for cultivation in regions where soil acidity is a recurrent constraint. Additionally, the wide variability observed among genotypes indicates substantial potential for continued selection toward acid tolerance and for the identification of materials with broad adaptation.

ACKNOWLEDGEMENTS

The authors thank the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) for the financial support provided through the 2023 Fiscal Project “Selección de genotipos de maíz y frijol negro tolerantes a la sequía terminal y adaptados a suelos ácidos de Veracruz y Tabasco”, as well as for the technical and logistical support that made this study possible.

REFERENCES

- García, E. 1973. Modificaciones al sistema de clasificación climática de Köppen. Instituto de Geografía, UNAM. México, D.F.
- Zetina, L. R.; Pastrana, A. L.; Romero, M. J. y Jiménez, C. J. A. 2002. Manejo de suelos ácidos para la región tropical húmeda de México (Libro Técnico Núm. 10). INIFAP-CIRGOC. Campos Experimentales Papaloapan y Huimanguillo. Veracruz, México.
- Zetina, L. R.; Trinidad, S. A.; Oropeza, M. J. L.; Volke, H. V. y Landois, P. L. L. 2005. Relación bases intercambiables - rendimiento de maíz en un cambisol dístico con labranza, enclado y abono verde. *Terra Latinoam.* 23(3):389-397.
- Dewi-Hayati, P.K.; Sutoyo, A.; Syarif, A.; Prasetyo, T. (2014). Performance of maize single-cross hybrids evaluated on acidic soils. *International Journal on Advanced Science, Engineering and Information Technology*, 4(3), 30-33.
- The, C., Calba, H., Zonkeng, C., Ngonkeu, E. L. M., Adetimirin, V. O., Mafouasson, H. A., ... & Horst, W. J. (2006). Responses of maize grain yield to changes in acid soil characteristics after soil amendments. *Plant and soil*, 284(1), 45-57. <https://doi.org/10.1007/s11104-006-0029-9>
- Ramírez-Sánchez, S., Hernández-Rodríguez, A., & López-Morales, J. (2020). Variabilidad genética en maíces tropicales bajo condiciones de acidez en suelo. *Revista Fitotecnia Mexicana*, 43(3), 245-256.
- Graham, R. D. 1984. Breeding for nutritional characteristics in cereals. *Adv. Plant Nutr.* 1, 57-102.
- Sierra, M. M., C. Ríos I., F. A. Rodríguez M., M. V. Vázquez H., O. H. Tosquy V. y P. Andrés M. 2019. Variedades sintéticas de maíz convencionales y de alta calidad de proteína en el área tropical del estado de Veracruz. p. 394-402. In: Vinay, V. J. C., V. A. Esqueda E., O. H. Tosquy V., R. Zetina L., A. Ríos U., M. V. Vázquez H., A. L. del Ángel P. y C. Perdomo M. (comps.). Avances en Investigación Agrícola, Pecuaria, Forestal, Acuícola, Pesquería, Desarrollo Rural, Transferencia de Tecnología, Biotecnología, Ambiente, Recursos Naturales y Cambio Climático. Libro Científico No. 1. Año 3. INIFAP. CP. UACH. INAPESCA. UV. TecNM. Medellín, Ver., México.

- Zetina, L. R.; Tosquy, V. O. H.; López, S. E.; Ibarra, P. F. J. y Morales, R. A. 2017. Adaptación de líneas recombinantes de frijol negro a suelos ácidos del sur de Veracruz. p. 251-259. En: Avances en Investigación Agrícola. (Libro Científico Núm. 1). INIFAP.
- Tandzi, L. N., Mutengwa, C. S., Ngonkeu, E. L. M., & Gracen, V. (2018). Breeding maize for tolerance to acidic soils: A review. *Agronomy*, 8(6), 84. <https://doi.org/10.3390/agronomy8060084>
- Ruíz, C. J. A.; Medina, G. G.; González, A. I. J.; Flores, L. H. E.; Ramírez, O. G.; Ortiz, T. C.; Byerly, M. K. F. y Martínez, P. R. A. 2013. Requerimientos agroecológicos de cultivos (Libro Técnico Núm. 3). INIFAP-CIRPAC. Campo Experimental Centro Altos de Jalisco. Tepatitlán de Morelos, Jalisco. 564 p.
- Palafox, C. A.; Sierra, M. M.; Rodríguez, F. A. M. y Ugalde, A. F. J. (2010). Tecnología de producción para maíz de grano y elote para el trópico húmedo de México (Folleto para Productores Núm. 14). INIFAP-CIRGOC. Campo Experimental Cotaxtla. Veracruz. 14 p.
- Olivares, S. E. (1994). Paquete estadístico de diseños experimentales (programa de cómputo) versión 2.5. Facultad de Agronomía de la Universidad Autónoma de Nuevo León.
- Kranz, W.L., S. Irmak, S.J. van Donk, C.D. Yonts, D.L. Martin. (2008). Irrigation Management for Corn (Neb Guide, G1850). University of Nebraska-Lincoln Extension. <https://extensionpublications.unl.edu/assets/pdf/g1850.pdf>
- Kochian, L. V., Piñeros, M. A., Liu, J., & Magalhaes, J. V. (2015). Plant adaptation to acid soils: The molecular basis for crop aluminum resistance. *Annual Review of Plant Biology*, 66, 571-598. <https://doi.org/10.1146/annurev-arplant-043014-114822>
- Von Uexküll, H. R., & Mutert, E. (1995). Global extent, development and economic impact of acid soils. *Plant and Soil*, 171, 1-15.
- Lestari, Y., Maas, A., Purwanto, B. H., & Utami, S. N. H. (2016). The influence of lime and nitrogen fertilizer on soil acidity, growth and nitrogen uptake of corn in total reclaimed potential acid sulphate soil. *Journal of Agricultural Science*, 8(12), 197-205. <https://doi.org/10.5539/jas.v8n12p197>
- Chairiyah, R. R., Ramija, K. E., & Batubara, S. F. (2021, July). Liming of acid soil and the interaction with soil pH and corn productivity. In IOP Conference Series: Earth and Environmental Science (Vol. 807, No. 4, p. 042071). IOP Publishing. <https://doi.org/10.1088/1755-1315/807/4/042071>
- Ochoa-Cadavid, I., Preciado-Ortíz, R. E., & Bayuelo-Jiménez, J. S. (2019). Interacción genotipo × ambiente y estabilidad en rendimiento de variedades de maíz bajo condiciones contrastantes de fósforo. *Agrociencia*, 53(3), 337-353.
- Tirado-Soto, C. S., Vásquez-Arce, V. A., & Narro-León, L. A. (2019). Stability of yield and adaptability of corn hybrids tolerant to acid soils based on the characteristics of the GGE biplot analysis. *ACI Avances en Ciencias e Ingenierías*, 11(1), 37-52. <https://doi.org/10.18272/aci.v11i1.1081>

Earliness and productive efficiency in tropical black bean genotypes (*Phaseolus vulgaris* L.) under terminal drought

Tosquy-Valle, Oscar H.¹; Zetina-Lezama, R.¹; Fadda, Lucas A.¹; Vázquez-Hernández, Marcos V.¹; Anaya-López, José L.^{2*}

¹ Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro de Investigación Regional Golfo Centro. Campo Experimental Cotaxtla. Medellín de Bravo, Veracruz, México. C. P. 91700.

² Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro de Investigación Regional Centro. Campo Experimental Bajío, Celaya, Guanajuato, México. C. P. 38110.

* Correspondence: anaya.jose@inifap.gob.mx

ABSTRACT

Objective: To determine the effect of earliness on grain yield of tropical black bean genotypes under terminal drought and to select those with lower susceptibility and higher productive efficiency than the cultivar Negro Jamapa.

Design/methodology/approach: Fifteen genotypes were evaluated using a randomized complete block design with three replications in two trials: one under full irrigation and another in which irrigation was suspended at the onset of flowering. Days to physiological maturity and grain yield were quantified. Analyses of variance were performed for each moisture regime, means were compared using the Least Significant Difference test ($\alpha=0.05$), and correlation analysis was conducted. Drought response was evaluated using the drought susceptibility index (DSI) and the relative efficiency index (REI).

Results: Verdín was the earliest genotype, reaching maturity at 72.3 and 68.0 days under full irrigation and drought stress, respectively. Papaloapan/SEN-46-7-10, CIAT-103-25, Jamapa Plus/XRAV-187-3-4-4, Papaloapan/SEN-46-2-6, and Rubí exhibited the lowest susceptibility to terminal drought (DSI<0.90), whereas Verdín, CIAT-103-25, and Jamapa Plus/XRAV-187-3-4-4 showed the highest productive efficiency (REI>1.28), surpassing Negro Jamapa. Grain yield was negatively correlated with days to maturity under both full irrigation ($r=-0.719^{**}$) and drought stress ($r=-0.557^{*}$).

Study Limitations/Implications: The selected genotypes constitute elite breeding materials; multi-environment evaluation is recommended.

Findings/conclusions: Earliness, as a drought escape mechanism, contributed significantly to productive efficiency under both moisture regimes. Five genotypes with the lowest susceptibility to terminal drought were selected, of which CIAT-103-25, Jamapa Plus/XRAV-187-3-4-4, and Verdín exhibited higher productive efficiency than Negro Jamapa.

Keywords: *Phaseolus vulgaris* L., drought resistance, drought escape, grain yield, tropical agriculture.

Citation: Tosquy-Valle, O. H., Zetina-Lezama, R., Fadda-Lucas, A., Vázquez-Hernández, M. V., & Anaya-López, J. L. (2026). Earliness and productive efficiency in tropical black bean genotypes (*Phaseolus vulgaris* L.) under terminal drought. *Agro Productividad*. <https://doi.org/10.32854/rss57727>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: November 26, 2025.

Accepted: January 13, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 67-77.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

In the humid tropical region of southeastern Mexico, terminal drought is the main environmental factor limiting common bean yield during the fall-winter growing season, when production depends on the last rains of the rainy season and on the residual moisture

stored in the soil profile (Tosquy-Valle *et al.*, 2018). Terminal drought periods have become more frequent and severe due to climate change (McClellan *et al.*, 2011; Chaves-Barrantes *et al.*, 2018). This results in significant reductions in essential yield components, including pods per plant, seeds per pod, and seed weight (Nuñez-Barrios *et al.*, 2005; Tosquy-Valle *et al.*, 2014), which ultimately leads to low grain production (Ghassemi-Golezani & Mardfar, 2008; Rosales *et al.*, 2012). Depending on its frequency, duration, and magnitude, terminal drought during the reproductive phase can reduce grain yield by more than 60% and, in extreme cases, cause total crop loss (López-Salinas *et al.*, 2011).

The use of drought-resistant varieties represents an effective strategy to mitigate yield losses caused by water deficit. Drought resistance in plants involves a series of adaptive strategies, which are commonly classified into three main mechanisms: escape, avoidance, and tolerance (Fang & Xiong, 2015; Bandurska, 2022). Drought escape involves completing the life cycle before the onset of severe stress, mainly through earliness or phenological adjustment (Kooyers, 2015). Drought avoidance refers to the ability of plants to maintain a favorable water status under stress through morphophysiological adaptations such as deep root development, reduction of leaf area, and efficient stomatal closure (Blum, 2011). By contrast, true drought tolerance is defined as the capacity of plants to endure cellular dehydration through mechanisms such as osmotic adjustment, synthesis of protective proteins, and membrane stabilization (Blum, 2017).

Although substantial progress has been made in identifying genotypes of tropical black bean with resistance to terminal drought (Tosquy-Valle *et al.*, 2014, 2016), further characterization is necessary to determine more precisely the effect of earliness on grain yield and productive efficiency under water-limited conditions. This information is essential to support breeding programs in the development of new varieties better adapted to terminal drought in tropical environments.

To select genotypes with resistance to water stress, conventional common bean breeding programs typically use the irrigation-drought methodology (Rosales-Serna *et al.*, 2000), which involves monitoring soil moisture availability throughout the crop cycle to determine the level of stress reached (Hillel, 1980) and to quantify the yield response of each genotype under contrasting moisture conditions (Tosquy-Valle *et al.*, 2018). In addition, various selection indices are used to identify materials with high productive efficiency under both well-watered and terminal drought conditions, characterized by minimal yield reduction when transitioning from optimal irrigation to water deficit (Fischer & Maurer, 1978).

Currently, the Common Bean Program of the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) in southeastern Mexico has developed improved varieties and advanced black bean lines. Some of these genotypes have been selected for their high yield potential and adaptation to tropical environments (Tosquy-Valle *et al.*, 2019), while others exhibit resistance to economically important diseases such as rust [*Uromyces appendiculatus* var. *appendiculatus* (Pers.) Unger], anthracnose [*Colletotrichum lindemuthianum* (Sacc. & Magnus) Lams. Scrib.], bean common mosaic virus (BCMV), and bean golden yellow mosaic virus (BGYMV) (Anaya-López *et al.*, 2018; Garrido-Ramírez *et al.*, 2020), all of which are frequently present in the main bean-producing areas of the region.

Therefore, the objective of this study was to determine the effect of earliness on grain yield in tropical black bean genotypes under terminal drought conditions and to select those with lower susceptibility and higher productive efficiency than the widely cultivated cultivar Negro Jamapa.

MATERIALS AND METHODS

Location and genetic material

Genotypes were evaluated in two field trials established during the winter-spring cropping cycle of 2024 on land located in La Colonia Ejidal, Cotaxtla, Veracruz, Mexico (18° 54' 53.39" N, 96° 13' 14.74" W; 22 m a.s.l.).

Both trials included 15 genotypes: ten advanced breeding lines from the INIFAP National Common Bean Program (five derived from the cross Papaloapan/SEN-46, three from Negro Citlali/XRAV-187-3, and two from Jamapa Plus/XRAV-187-3), line CIAT-103-25 from the International Center for Tropical Agriculture (CIAT, Cali, Colombia), and four improved cultivars developed by INIFAP for tropical areas of southeastern Mexico: Verdín, Rubí, Rincón Grande, and Negro Jamapa as the regional check (Tosquy-Valle *et al.*, 2016; 2025; Ibarra-Pérez *et al.*, 2022).

Trial establishment and irrigation treatments

Both trials were planted on January 26, 2024, at a density of 250,000 plants ha⁻¹, using a randomized complete block design with three replications. Each plot consisted of three 5-m-long rows spaced 0.80 m apart; the central row was considered the useful plot. One trial was maintained under full irrigation throughout the crop cycle. A total of seven irrigations were applied, the first at pre-planting and subsequent applications at intervals of 11 to 15 days, depending on soil moisture conditions. The total irrigation depth applied was approximately 350 mm. In the second trial, only four irrigations were applied, with a total irrigation depth of approximately 200 mm. Irrigation was suspended 42 days after planting, when most genotypes had initiated flowering, in order to induce terminal drought conditions.

Soil moisture determination

In both trials, soil samples were collected at depths of 0-15 and 15-30 cm every 10 days, from planting until crop maturity, to determine moisture content using the gravimetric method (Caicedo-Rosero *et al.*, 2021). Additional soil samples were collected from the 0-30 cm layer to determine permanent wilting point (PWP) and field capacity (FC), allowing the estimation of available soil moisture under both moisture regimes, where 0% corresponded to PWP and 100% to FC (Walters, 2021).

Available soil moisture values were plotted to evaluate their dynamics before and after flowering under both moisture conditions. Terminal drought was considered to occur when available soil moisture fell below 45% (Allen *et al.*, 2006).

Agronomic management

Fertilization, weed control, pest management, and harvest were carried out in accordance with the recommendations of López-Salinas *et al.* (2017) for common bean

production in Veracruz. Throughout the crop cycle, no diseases occurred that affected plant development or grain yield in either the fully irrigated or terminal drought trial.

Variables evaluated and statistical analysis

The variables evaluated were: days to physiological maturity, recorded from planting until 50% of the plants of each genotype exhibited yellow-colored pods, and grain yield (kg ha^{-1}), estimated from harvested and cleaned grain from each plot and adjusted to 14% moisture content.

Analyses of variance were performed separately for each moisture condition, and mean comparisons were conducted using the Least Significant Difference (LSD) test ($\alpha=0.05$). In addition, correlation analyses were carried out among the variables evaluated under each moisture condition (Olivares, 1994).

Assessment of drought impact

The effect of drought on the mean yield of each genotype was estimated using the drought susceptibility index (DSI; Fischer & Maurer, 1978) and the relative efficiency index (REI), both widely used in drought-resistance studies (Bennani *et al.*, 2017; Basavaraj *et al.*, 2025). The following variables were used for index calculation: Y_{si} = mean yield of genotype i under stress, Y_{ni} = mean yield of genotype i under non-stress conditions, Y_s = mean yield of all genotypes under stress, and Y_n = mean yield of all genotypes under non-stress conditions.

DSI was calculated as $DSI_i = (1 - Y_{si} / Y_{ni}) / DII$, where the drought intensity index was obtained as $DII = 1 - (Y_s / Y_n)$. DSI is a function of yield reduction caused by drought; a value of 1 indicates medium susceptibility, values greater than 1 indicate susceptible genotypes, and values close to zero indicate lower drought susceptibility (Fischer & Maurer, 1978).

REI was calculated as $REI_i = (Y_{si} / Y_s) \times (Y_{ni} / Y_n)$. This index allows classification of genotypes on the basis of their performance under both moisture conditions; higher values indicate greater productive efficiency and better relative performance (Basavaraj *et al.*, 2025).

RESULTS AND DISCUSSION

Soil moisture and stress conditions

From planting to the flowering stage, both trials showed similar patterns in soil moisture content, with an average of 96% available water. During this period, soil water depletion did not exceed 45%, the threshold at which common bean begins to experience stress (Allen *et al.*, 2006). Upon suspending irrigation in the terminal drought trial, available moisture declined gradually as the crop progressed toward physiological maturity (Figure 1).

At physiological maturity in this trial, moisture content averaged 26.4%, indicating that plants were subjected to water stress during most of the reproductive phase. This did not occur in the irrigated trial, where available moisture remained above the critical threshold throughout the entire cycle, averaging 88%.

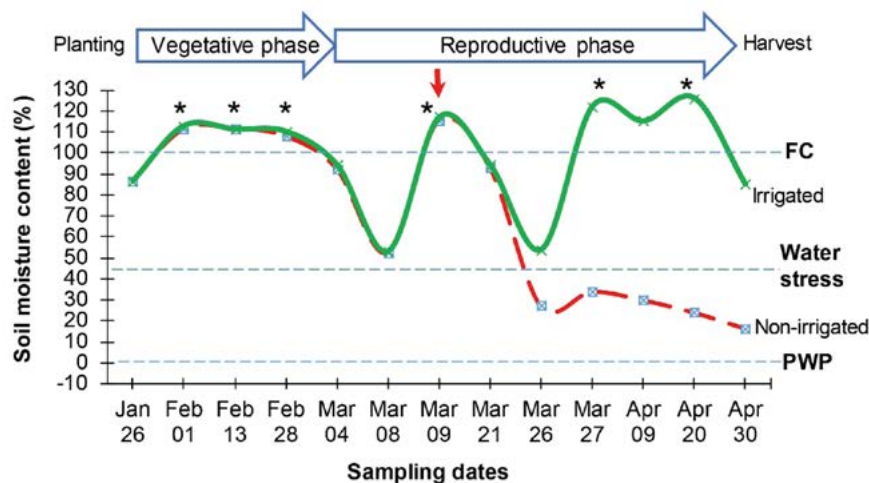


Figure 1. Available moisture in the topsoil layer (0-30 cm) during common bean development in the irrigated and terminal drought trials established at La Colonia Ejidal, Cotaxtla, Veracruz, during the winter-spring 2024 cycle. Blue dotted lines show the percentage of soil moisture at field capacity (FC), under water stress, and at permanent wilting point (PWP). Asterisks indicate irrigation dates, and the red arrow indicates irrigation suspension in the drought trial.

Earliness and grain yield

In both trials, statistical significance was detected among treatments ($P \leq 0.01$ or 0.05) for both variables quantified (Table 1), indicating that genotypes differed both in the timing of physiological maturity and in their productive capacity under irrigated and terminal drought conditions.

Under both moisture conditions, the cultivar Verdín was the earliest to reach physiological maturity, with timing statistically similar to the cultivar Rubí and the lines Papaloapan/SEN-46-3-2 and Negro Citlali/XRAV-187-3-1-8 under full irrigation, and significantly shorter than the rest of the genotypes under terminal drought (Table 2). Terminal drought stress reduced days to maturity by an average of 6.47% across all genotypes, equivalent to 5.0 days; the cultivars Verdín and Rubí, along with five other lines, showed reduction percentages below the overall average, whereas the cultivar Rincón Grande and the line Papaloapan/SEN-46-7-7 were the most affected for this

Table 1. Mean squares and statistical significance of variables quantified in trials conducted under full irrigation and terminal drought during the crop cycle at La Colonia Ejidal, Cotaxtla, Veracruz. Winter-spring cycle of 2024.

SV	DF	Full irrigation		Terminal drought	
		DPM [†]	GY [‡]	DPM [†]	GY [‡]
Treatments	14	26.25 **	188926.28**	8.58 **	133609.42 *
Blocks	2	0.47	32704.00	4.86	41350.00
Error	28	2.30	51611.14	1.39	59156.00
Total	44				
CV (%)		1.96	15.88	1.63	21.60

SV: Source of variation. DF: Degrees of freedom. [†]DPM: Days to physiological maturity. [‡]GY: Grain yield. *Significant at $P \leq 0.05$; **Significant at $P \leq 0.01$.

Table 2. Effect of terminal drought stress on days to physiological maturity of black bean genotypes evaluated under full irrigation throughout the crop cycle and with irrigation suspension at flowering initiation. La Colonia Ejidal, Cotaxtla, Veracruz, Mexico. Winter-spring cycle of 2024.

Genotype	Physiological maturity (days)		
	Full irrigation	Terminal drought	Reduction (%) [†]
Papaloapan/SEN-46-2-6	77.67cde	73.33ab	5.59
Papaloapan/SEN-46-3-2	74.67fgh	73.33ab	1.79
Papaloapan/SEN-46-7-7	82.33a	73.67a	10.52
Papaloapan/SEN-46-7-10	79.00bcd	72.67abcd	8.01
Papaloapan/SEN-46-7-12	80.67ab	74.00a	8.27
Negro Citlali/XRAV-187-3-1-5	75.67efg	73.33ab	3.09
Negro Citlali/XRAV-187-3-1-6	76.00efg	73.67a	3.07
Negro Citlali/XRAV-187-3-1-8	74.33fgh	70.00e	5.82
Rincón Grande	80.00abc	71.33cde	10.84
Jamapa Plus/XRAV-187-3-4-1	80.67ab	73.67a	8.68
Jamapa Plus/XRAV-187-3-4-4	76.00efg	71.33cde	6.14
CIAT-103-25	79.33bc	73.00abc	7.98
Negro Jamapa (RC)	76.67def	71.00de	7.39
Verdín	72.33h	68.00f	5.99
Rubí	73.67gh	71.67bcde	2.71
Mean ^{††}	77.27	72.27	6.47
LSD (0.05)	2.54	1.97	
Correlation (r) with GY [‡]	-0.719**	-0.557*	

[†]Percentage reduction due to terminal drought stress. ^{††}Mean days to physiological maturity under full irrigation and terminal drought. [‡]Correlation coefficient with grain yield. RC: regional check. Means followed by different letters within a column are significantly different according to LSD ($\alpha=0.05$).

trait (Table 2). This phenomenon occurs because water stress prematurely induces leaf senescence to accelerate nutrient remobilization toward reproductive structures (Labastida *et al.*, 2023).

Generally, common bean genotypes that perform well under drought conditions also perform well without moisture stress (Szilagyi, 2003; Beebe *et al.*, 2008). This premise held true in this study, as most genotypes that excelled in yield under irrigated conditions also performed well under terminal drought. The cultivar Verdín was the most productive under both moisture conditions, followed by the lines CIAT-103-25 and Jamapa Plus/XRAV-187-3-4-4, whereas the lines Papaloapan/SEN-46-7-12 and Papaloapan/SEN-46-7-7 yielded the lowest under both moisture regimes (Table 3). The high productivity of Verdín in environments with and without terminal drought has been documented in other evaluation studies of black bean genotypes under residual moisture conditions in Veracruz and Chiapas (Tosquy-Valle *et al.*, 2018).

Under both irrigated and terminal drought conditions, days to physiological maturity were negatively and significantly correlated with grain yield ($r=-0.719^{**}$ and -0.557^{*}). This correlation suggests that earliness may have functioned as a drought-escape mechanism, allowing completion of the reproductive cycle before severe water

Table 3. Effect of terminal drought stress on grain yield of black bean genotypes evaluated under full irrigation throughout the crop cycle and with irrigation suspension at flowering initiation, and estimated drought susceptibility (DSI) and relative efficiency (REI) indices. La Colonia Ejidal, Cotaxtla, Veracruz, Mexico. Winter-spring cycle of 2024.

Genotype	Grain yield (kg ha ⁻¹)			DSI	REI
	Full irrigation	Terminal drought	Reduction (%) [†]		
Papaloapan/SEN-46-2-6	1480.00abc	1198.33ab	19.03	0.89	1.10
Papaloapan/SEN-46-3-2	1581.67ab	1215.00ab	23.18	1.09	1.19
Papaloapan/SEN-46-7-7	1033.33de	768.33cd	25.64	1.20	0.49
Papaloapan/SEN-46-7-10	1106.67cde	1000.00bcd	9.64	0.45	0.69
Papaloapan/SEN-46-7-12	838.33e	645.00d	23.06	1.08	0.34
Negro Citlali/XRAV-187-3-1-5	1538.33ab	1211.67ab	21.23	1.00	1.16
Negro Citlali/XRAV-187-3-1-6	1486.67ab	1088.33abc	26.79	1.26	1.00
Negro Citlali/XRAV-187-3-1-8	1570.00ab	1260.00ab	19.74	0.93	1.23
Rincón Grande	1430.00abc	1093.33abc	23.54	1.10	0.97
Jamapa Plus/XRAV-187-3-4-1	1450.00abc	1040.00abcd	28.28	1.33	0.94
Jamapa Plus/XRAV-187-3-4-4	1601.67ab	1300.00ab	18.83	0.88	1.29
CIAT-103-25	1630.00ab	1343.33ab	17.59	0.83	1.36
Negro Jamapa (RC)	1380.00bcd	1020.00abcd	26.09	1.22	0.87
Verdín	1781.67a	1418.33a	20.39	0.96	1.57
Rubí	1546.67ab	1286.67ab	16.81	0.79	1.23
Mean ^{††}	1430.33a	1125.89b	21.28		
LSD (0.05)	379.89	406.71			

[†]Percentage reduction due to terminal drought stress. ^{††}Mean grain yield under full irrigation and terminal drought. DSI: Drought susceptibility index. REI: Relative efficiency index. RC: regional check. Means followed by different letters within a column are significantly different according to LSD ($\alpha=0.05$).

deficits (Beebe *et al.*, 2008; Zilio *et al.*, 2013), rather than as true tolerance based on physiological mechanisms such as osmotic adjustment or deeper root systems (Polania *et al.*, 2016).

The early maturity of Verdín and Rubí represents an adaptive advantage under terminal drought by allowing plants to complete their cycle before water-deficit periods that generally occur at the end of the reproductive phase (Acosta-Díaz *et al.*, 2004). In addition to reducing risks of yield loss from the occurrence of terminal drought, early genotypes allow producers to obtain greater bean production in less time, with or without terminal water stress (Tosquy-Valle *et al.*, 2018), possibly through greater efficiency in the partitioning of dry matter to the grain (Rao *et al.*, 2016). This escape strategy has been extensively documented in wheat, where high yield potential has also been observed due to the development of both shallow and deep roots, representing plasticity in response to drought combined with early flowering (Ehdaie *et al.*, 2012; Shavrukov *et al.*, 2017). In this study, morphophysiological traits and root characteristics were not evaluated; therefore, the specific contribution of each mechanism to the observed response requires additional investigation.

Terminal drought susceptibility and productive efficiency

During the trials, no rainfall occurred that modified the terminal drought condition. The drought intensity index (DII) was 0.21, equivalent to an average grain yield reduction of 304.4 kg ha^{-1} compared to the irrigated condition. This value corresponds to moderate water stress and is comparable to that reported by Wasae (2021) during pod filling (DII=0.25) and Darkwa *et al.* (2016) for terminal drought in Ethiopia (DII=0.30), who also classified these levels as moderate stress.

Although this level is lower than that considered severe (DII>0.60; Ramírez-Vallejo & Kelly, 1998), it is representative of the range of terminal drought intensities occurring in the humid tropics of southeastern Mexico. For instance, López-Salinas *et al.* (2011) reported a DII of 0.62 under severe drought conditions in Veracruz, reflecting the variability in stress intensity that can manifest in the region. This variability depends on factors such as the duration of periods without rainfall and residual soil moisture, characteristics of a region with high vulnerability to drought (Ortega-Gaucin *et al.*, 2018). The moderate stress level evaluated is relevant for identifying genotypes with a favorable response to terminal drought that commonly occurs in bean plantings in the southeastern region and allowed differentiation of genotype responses, with yield reductions ranging from 9.64% to 28.28% (Table 3).

The lines Papaloapan/SEN-46-7-10, CIAT-103-25, Jamapa Plus/XRAV-187-3-4-4, Papaloapan/SEN-46-2-6, and the cultivar Rubí showed the lowest susceptibility to terminal water stress, obtaining drought susceptibility index (DSI) values closest to zero. Meanwhile, the lines Jamapa Plus/XRAV-187-3-4-1, Negro Citlali/XRAV-187-3-1-6, Papaloapan/SEN-46-7-7, and the cultivar Negro Jamapa were the most susceptible, with DSI values exceeding 1.0 (Table 3), indicating that they exhibited the highest percentages of grain yield reduction due to terminal drought (Fischer & Maurer, 1978). It is important to note that genotypes with low DSI values are not necessarily the most productive, as occurred in this study, where the line Papaloapan/SEN-46-7-10, which showed the lowest drought susceptibility (DSI=0.45), did not exhibit significantly outstanding grain yield under either full irrigation or terminal drought (Table 3). A similar situation was reported by Tosquy-Valle *et al.* (2014) with other opaque black bean genotypes of the Mesoamerican race from CIAT and the University of Puerto Rico.

Among the genotypes showing the lowest terminal drought susceptibility, the lines CIAT-103-25 and Jamapa Plus/XRAV-187-3-4-4, together with the cultivar Verdín, obtained the highest relative efficiency index (REI) values, indicating high grain yield under both moisture conditions, whereas the lines Papaloapan/SEN-46-7-12, Papaloapan/SEN-46-7-7, and Papaloapan/SEN-46-7-10 showed the lowest productive efficiency, with REI values well below 1.0 (Table 3). The ideal scenario is to have bean genotypes that exhibit low yield reduction under terminal water stress and high productive efficiency under both full irrigation and terminal drought.

Selected genotypes require multi-environment validation across diverse locations and cycles in the humid tropics to confirm their stability. Future research should include characterization of morphophysiological traits (root system, pod harvest index, water-use

efficiency) and molecular analyses to elucidate possible specific tolerance mechanisms (Wu *et al.*, 2024).

In practical terms, Verdín is commercially available (Tosquy-Valle *et al.*, 2016), whereas CIAT-103-25 and Jamapa Plus/XRAV-187-3-4-4 require additional validation cycles before becoming available as cultivars or can be used as parents in breeding programs for terminal drought resistance. The earliness of these materials offers additional advantages: lower production costs, the possibility of relay cropping, and reduced exposure to late-cycle pests.

CONCLUSIONS

Earliness functions as an effective escape mechanism to terminal drought in tropical black bean, explaining the differences in productive efficiency among genotypes. Three elite materials were selected that combine earliness, low drought susceptibility, and high productive efficiency under both full irrigation and terminal drought conditions: the cultivar Verdín (commercially available) and the lines CIAT-103-25 and Jamapa Plus/XRAV-187-3-4-4, which represent superior alternatives to Negro Jamapa in the humid tropics. These findings confirm that selection for a short crop cycle is a practical and effective strategy for developing cultivars adapted to terminal drought. The characterization of complementary physiological mechanisms would enable optimization of future breeding strategies.

ACKNOWLEDGMENTS

The authors thank the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) for the financial support provided to carry out this research through the project “Selection of maize and black bean genotypes tolerant to terminal drought and adapted to acid soils of Veracruz and Tabasco”, registered in the Institutional Integrated Management System (SIGI) under number 14374635653.

REFERENCES

- Acosta-Díaz, E., Trejo-López, C., Ruíz-Posadas, L.M., Padilla-Ramírez, J.S., & Acosta-Gallegos, J.A. (2004). Adaptación del frijol a sequía en la etapa reproductiva. *Terra Latinoamericana*, 22(1), 49-58.
- Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (2006). Evapotranspiración del cultivo. Guías para la determinación de los requerimientos de agua de los cultivos. Estudio FAO. Riego y Drenaje No. 56. Organización de las Naciones Unidas para la Agricultura y la Alimentación. Roma, Italia. 298 p.
- Anaya-López, J.L., Garrido-Ramírez, E.R., Chiquito-Almanza, E., Tosquy-Valle, O.H., Ibarra-Pérez, F.J., & López-Salinas, E. (2018). Identificación de líneas recombinantes de frijol negro opaco resistentes a BCMV, BCMNV y BGYMV mediante marcadores moleculares. *Revista Mexicana de Ciencias Agrícolas*, 9(3), 601-614. <https://dx.doi.org/10.29312/remexca.v9i3.1219>.
- Bandurska, H. (2022). Drought stress responses: Coping strategy and resistance. *Plants* 11(7):922. <https://doi.org/10.3390/plants11070922>.
- Beebe, S., Rao, I., Cajao, C., & Grajales, M. (2008). Selection for drought resistance in common bean also improves yield in phosphorus limited and favorable environments. *Crop Science*, 48(2), 582-592. <https://doi.org/10.2135/cropsci2007.07.0404>.
- Caicedo-Rosero, L.C., Méndez-Ávila, F.J., Gutiérrez-Zeferino, E., & Flore-Cuautle, J.J.A. (2021). Medición de humedad en suelos: revisión de métodos y características. *Pádi Boletín Científico de Ciencias Básicas e Ingenierías del ICBI*, 9(17), 1-8. <https://doi.org/10.29057/icbi.v9i17.7035>.
- Chaves-Barrantes, N.F., Polanía, J.A., Muñoz-Perea, C.G., Rao, I.M., & Beebe, S.E. (2018). Caracterización fenotípica por resistencia a sequía terminal de germoplasma de frijol común. *Agronomía Mesoamericana*, 29(1), 1-17. <https://doi.org/10.15517/ma.v29i1.27618>.

- Darkwa, K., Ambachew, D., Mohammed, H., Asfaw, A., & Blair, M.W. (2016). Evaluation of common bean (*Phaseolus vulgaris* L.) genotypes for drought stress adaptation in Ethiopia. *The crop journal*, 4(5), 367-376. <https://doi.org/10.1016/j.cj.2016.06.007>.
- Ehdaie, B., Layne, A.P., & Waines, J.G. (2012). Root system plasticity to drought influences grain yield in bread wheat. *Euphytica* 186, 219-232. <https://doi.org/10.1007/s10681-011-0585-9>.
- Fang, Y., & Xiong, L. (2015). General mechanisms of drought response and their application in drought resistance improvement in plants. *Cellular and molecular life sciences*, 72(4), 673-689. <https://doi.org/10.1007/s00018-014-1767-0>.
- Fischer, R.A., & Maurer, R. (1978). Drought resistance in spring wheat cultivars. I. Grain yield responses. *Australian Journal of Agricultural Research*, 29(5), 897-912. <https://dx.doi.org/10.1071/ar9780897>.
- Garrido-Ramírez, E.R., Tosquy-Valle, O.H., Esqueda-Esquivel, V.A., Ibarra-Pérez, F.J., Rodríguez-Rodríguez, J.R., & Villar-Sánchez, B. (2020). Identification of black bean (*Phaseolus vulgaris* L.) genotypes resistant to anthracnose and rust for Veracruz and Chiapas, Mexico. *Agro Productividad*, 13(8), 79-84. <https://doi.org/10.32854/agrop.vi.1719>.
- Ghassemi-Golezani, K., & Mardfar, R.A. (2008). Effects of limited irrigation and grain yield of common bean. *Journal of Plant Sciences*, 3(3), 230-235. <https://doi.org/10.3923/jps.2008.230.235>.
- Hillel, D. (1980). Applications of soil physics. 1st ed. Academic Press. New York, USA. 385 p.
- Ibarra-Pérez, F.J., Tosquy-Valle, O.H., Rodríguez-Rodríguez, J.R., Villar-Sánchez, B., López-Salinas, E., & Anaya-López, J.L. (2022). Rubí: nueva variedad mejorada de frijol negro para las áreas tropicales de Veracruz y Chiapas. *Revista Mexicana de Ciencias Agrícolas*, 13(3), 577-585. <https://doi.org/10.29312/remexca.v13i3.2227>.
- Kooyers, N.J. (2015). The evolution of drought escape and avoidance in natural herbaceous populations. *Plant science*, 234, 155-162. <https://doi.org/10.1016/j.plantsci.2015.02.012>.
- Labastida, D., Ingvarsson, P.K., & Rendón-Anaya, M. (2023). Dissecting the genetic basis of drought responses in common bean using natural variation. *Frontiers in Plant Science*, 14, 1143873. <https://doi.org/10.3389/fpls.2023.1143873>.
- López-Salinas, E., Tosquy-Valle, O.H., & Ibarra-Pérez, F.J. (2017). Frijol. p. 33-36. In: Zetina, L. R. y S. Uribe G. (comps.). Agenda Técnica Agrícola Veracruz. SAGARPA. INIFAP. COFUPRO. México, D. F.
- López-Salinas, E., Tosquy-Valle, O.H., Acosta-Gallegos, J.A., Villar-Sánchez, B., & Ugalde-Acosta, F.J. (2011). Drought resistance of tropical dry black bean lines and cultivars. *Tropical and Subtropical Agroecosystems*, 14(2), 749-755.
- McClellan, P.E., Burrridge, J., Beebe, S., Rao, I.M., & Porch, T.G. (2011). Crop improvement in the era of climate change: an integrated, multi-disciplinary approach for common bean (*Phaseolus vulgaris*). *Functional Plant Biology*, 38(12), 927-933. <https://doi.org/10.1071/FP11102>.
- Nuñez-Barrios, A., Hoogenboom, G., & Nesmith, D.S. (2005). Drought stress and the distribution of vegetative and reproductive traits of a bean cultivar. *Crop Science, Scientia Agricola (Piracicaba, Braz.)*, 62(1), 18-22. <https://doi.org/10.1590/S0103-90162005000100004>.
- Olivares, S.E. (1994). Paquete estadístico de diseños experimentales (programa de cómputo) versión 2.5. Facultad de Agronomía de la Universidad Autónoma de Nuevo León. Marín, N. L., México.
- Ortega-Gaucin, D., De la Cruz Bartolón, J. & Castellano Bahena, H.V. (2018). Drought vulnerability indices in Mexico. *Water*, 10(11), 1671. <https://doi.org/10.3390/w10111671>.
- Polania, J.A., Poschenrieder, C., Beebe, S., & Rao, I.M. (2016). Effective use of water and increased dry matter partitioned to grain contribute to yield of common bean improved for drought resistance. *Frontiers in Plant Science*, 7, 660. <https://doi.org/10.3389/fpls.2016.00660>.
- Ramírez-Vallejo, P., & Kelly, J.D. (1998). Traits related to drought resistance in common bean. *Euphytica*, 99, 127-136. <https://doi.org/10.1023/A:1018353200015>.
- Rao, I.M., Beebe, S.E., Polania, J., Grajales, M., Cajiao, C., Ricaurte, J., García, R. & Rivera, M. (2016). Evidence for genotypic differences among elite lines of common bean in the ability to remobilize photosynthate to increase yield under drought. *The Journal of Agricultural Science*, 155(6), 857-875. <https://doi.org/10.1017/S0021859616000915>.
- Rosales, M.A., Ocampo, E., Rodríguez-Valentín, R., Olvera-Carrillo, Y., Acosta-Gallegos, J.A., & Covarrubias, A.A. (2012). Physiological analysis of common bean (*Phaseolus vulgaris* L.) cultivars uncovers characteristics related to terminal drought resistance. *Plant Physiology and Biochemistry*, 56, 24-34. <https://doi.org/10.1016/j.plaphy.2012.04.007>.
- Rosales-Serna, R., Ramírez-Vallejo, P., Acosta-Gallegos, J.A., Castillo-González, F., & Kelly, J.D. (2000). Rendimiento de grano y tolerancia a la sequía del frijol común en condiciones de campo. *Agrociencia*, 34(2), 153-165.

- Shavrukov, Y., Kurishbayev, A., Jatayev, S., Shvidchenko, V., Zotova, L., Koekemoer, F., de Groot, Soole, K., & Langridge, P. (2017). Early flowering as a drought escape mechanism in plants: How can it aid wheat production? *Frontiers in Plant Science*, 8, 1950. <https://doi.org/10.3389/fpls.2017.01950>.
- Szilagy, L. (2003). Influence of drought on seed yield components in common bean. *Bulgarian Journal of Plant Physiology*, Special Issue, 320-330.
- Tosquy-Valle, O.H., Ibarra-Pérez, F.J., Acosta-Gallegos, J.A., Esqueda-Esquivel, V.A., & Anaya-López, J.L. (2025). Rincón Grande: variedad de frijol negro para Veracruz y Chiapas. *Revista Mexicana de Ciencias Agrícolas*, 16(3), e3646. <https://doi.org/10.29312/remexca.v16i3.3646>.
- Tosquy-Valle, O.H., López-Salinas, E., Francisco-Nicolás, N., Acosta-Gallegos J.A., & Villar-Sánchez, B. (2014). Genotipos de frijol negro opaco resistentes a sequía terminal. *Revista Mexicana de Ciencias Agrícolas*, 5(7), 1205-1217. <https://doi.org/10.29312/remexca.v5i7.866>.
- Tosquy-Valle, O.H., López-Salinas, E., Villar-Sánchez, B., Acosta-Gallegos, J.A., & Rodríguez-Rodríguez, J.R. (2016). Verdín: variedad de frijol negro tolerante a sequía terminal para Veracruz y Chiapas, México. *Revista Mexicana de Ciencias Agrícolas*, 7(7), 1775-1780. <https://doi.org/10.29312/remexca.v7i7.170>.
- Tosquy-Valle, O.H., López-Salinas, E., Villar-Sánchez, B., Zetina-Lezama, R., Acosta-Gallegos, J.A., Rodríguez-Rodríguez, J.R., & Ibarra-Pérez, F.J. (2018). Rendimiento y adaptación de genotipos de frijol negro opaco en ambientes con y sin sequía terminal. *Revista Mexicana de Ciencias Agrícolas*, 9(4), 827-839. <https://doi.org/10.29312/remexca.v9i4.1399>.
- Tosquy-Valle, O.H., Villar-Sánchez, B., Rodríguez-Rodríguez, J.R., Ibarra-Pérez, F.J., Zetina-Lezama, R., Meza, P.A., & Anaya-López, J.L. (2019). Adaptación de genotipos de frijol negro a diferentes ambientes de Veracruz y Chiapas. *Revista Mexicana de Ciencias Agrícolas*, 10(6), 1301-1312. <https://doi.org/10.29312/remexca.v10i6.1658>.
- Walters, R. (2021). Ag Water Literacy III (Technical Note 7). CPF Global Agronomics & NCSU Department of Biological and Agricultural Engineering. https://agrosphere-international.net/Documents/DHC/Ag_Water_Literacy_PIII.pdf
- Wasae, A. (2021). Evaluation of drought stress tolerance based on selection indices in haricot bean varieties exposed to stress at different growth stages. *International Journal of Agronomy*, 2021(1), 6617874. <https://doi.org/10.1155/2021/6617874>.
- Wu, L., Chang, Y., Wang, L., Wang, S., & Wu, J. (2024). Genome-wide association study dissecting drought resistance-associated loci based on physiological traits in common bean. *Journal of Integrative Agriculture*, 23(11), 3657-3671. <https://doi.org/10.1016/j.jia.2024.03.079>.
- Zilio, M., Arruda, C., Medeiros, C.M., Miquelluti, D., & Ferreira, A. (2013). Cycle, canopy architecture and yield of common bean genotypes (*Phaseolus vulgaris*) in Santa Catarina State, Brazil. *Acta Scientiarum Agronomy*, 35(1), 21-30. <https://doi.org/10.4025/actasciagron.v35i1.15516>.

Efficacy of *Beauveria bassiana* as a biopesticide: A meta-analysis

Ramírez-Guerrero, Angélica A.¹; Marmolejo-Rodríguez, José M.¹; Macías-Gómez, Nelly M.¹; Montañez-Valdez, Oziel D.²; González-Villaseñor, Christian O.¹

¹ Universidad de Guadalajara, Centro Universitario del Sur, Centro de Investigación en Biología Molecular de las Enfermedades Crónicas, Ciudad Guzmán, Jalisco, México. C.P. 49000.

² Universidad de Guadalajara, Centro Universitario del Sur, Grupo de Investigación en Nutrición Animal, Ciudad Guzmán, Jalisco, México. C.P. 49000.

* Correspondence: christiang@cusur.udg.mx

ABSTRACT

Objective: To perform a meta-analysis evaluating the efficacy of *Beauveria bassiana* as a biological control agent against agricultural pests.

Methodology: A bibliographic search was conducted using the Embase and PubMed databases, applying the terms *Beauveria bassiana*, entomopathogenic fungi, crop, plant, and mortality, connected by the operator “AND.” The search encompassed studies published from 2019 to 2024. The analysis focused primarily on reported mortality rates, crop species treated, conidial concentrations, and targeted pest species.

Results: The most frequently applied conidial concentration was 1×10^8 conidia/mL. Mortality rates ranging from 25% to 75% were the most commonly reported, particularly in trials targeting Hemipteran pests, where favorable outcomes were consistently observed.

Limitations: There was notable variability across studies in terms of fungal concentration, crop type, application technique, and reproducibility of laboratory results, which may affect the generalizability of findings.

Conclusions: The use of *Beauveria bassiana* is recommended for the control of Hemipteran pests, given the consistently high mortality rates reported. Additionally, its potential as a biocontrol agent for mites is proposed, although further evidence is required to support this application. Conidial concentrations of 1×10^7 and 1×10^8 conidia/mL are suggested, preferably utilizing locally adapted *Beauveria bassiana* strains.

Keyword: Biopesticide, entomopathogenic fungus, biological control, agriculture.

Citation: Ramírez-Guerrero, A. A., Marmolejo-Rodríguez, J. M., Macías-Gómez, N. M., Montañez-Valdez, O. D., & González-Villaseñor, C. O. (2026). Efficacy of *Beauveria bassiana* as a biopesticide: A meta-analysis. *Agro Productividad*. <https://doi.org/10.32854/p2t1jy06>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

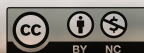
Received: November 10, 2025.

Accepted: January 30, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 79-88.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Agriculture remains one of the main sources of income in several countries, particularly those with favorable climates for diverse crop cultivation. According to data from the World Bank, agricultural crop revenues contribute up to 25% of the gross domestic product (GDP) in certain nations, while in countries with limited arable land or less suitable climatic conditions, this contribution drops to approximately 4% of GDP (World Bank, 2024). Compared to other productive sectors, agriculture faces



a wide range of challenges that can negatively impact crop growth, fruit development, and, ultimately, harvest yields. Key factors influencing agricultural productivity include climate change (*e.g.*, temperature fluctuations), soil quality, water availability (*e.g.*, droughts or floods), and inefficient irrigation practices often linked to poor human management (FAO, 2023).

These are compounded by nutrient availability, plant pathogens, and insect infestations—one of the leading causes of crop and economic losses worldwide. Insects alone are responsible for up to 40% of global crop losses, posing a major threat to the sustainability of the agricultural sector (FAO, 2020). Consequently, a significant portion of agricultural investment is directed toward pest control, with over \$30 billion spent annually on chemical pesticides. These substances, while effective, pose risks to human health, especially to farmers and consumers. In 2014, the World Health Organization (WHO) estimated approximately 100,000 deaths per year due to pesticide exposure, with an additional 200,000 cases of poisoning linked to improper use (OPS, UNEP, FAO, and MSP, 2014). More recently, these figures have increased, contributing to rising incidence rates of pesticide-related diseases across all age groups. Notably, in rural areas, children are particularly vulnerable, with evidence linking pesticide exposure to neurodevelopmental disorders and increased risk of cancers such as leukemia. In neonates, exposure has been associated with congenital malformations and behavioral abnormalities (Boedeker *et al.*, 2024; UNICEF, 2022). Studies conducted between 2002 and 2012 confirmed a significant association between pesticide exposure and neurological impairments in children, including cognitive, behavioral, and motor deficits.

These were manifested through reduced attention, memory, learning ability, concentration, and reflexes attributed to the neurotoxic effects of these chemicals (Muñoz-Quezada *et al.*, 2013). Beyond health implications, indiscriminate pesticide use, inadequate management, and inconsistent international regulations have had severe environmental consequences. These include contamination of soils and water bodies with pesticide residues. Silva *et al.* (2019) analyzed 317 soil samples from agricultural lands and detected pesticide residues in 83% of them; among these, 58% contained between two and over ten distinct chemical residues.

In light of these issues, numerous innovative alternatives for pest control have emerged. These include the use of bacteria, entomopathogenic nematodes (EPNs), sterile insect techniques, entomopathogenic fungi (EPFs), viruses, protozoa, natural predators such as insects, arachnids, and some vertebrates, parasitic organisms, and biochemicals like pheromones or growth regulators, all of which have shown promising results. Among these, entomopathogenic fungi have attracted considerable attention due to their ability to control various pest species. Although over 90 genera and more than 700 EPF species have been identified, only a few have been extensively studied. *Metarhizium anisopliae* stands out for its high virulence and commercial success. Similarly, *Beauveria bassiana* has garnered research interest due to its potential as an insect control agent across a range of crops. Therefore, the aim of this review is to summarize and discuss current knowledge on *B. bassiana* as a biological pest control tool.

MATERIALS AND METHODS

A comprehensive literature review was conducted using the PubMed and Embase search engines. The selection criteria included articles published between January 1, 2019, and November 1, 2024. The search employed the keywords *Beauveria bassiana*, entomopathogenic fungi, crop, plant, and mortality, connected using the operator “AND.” In Embase, the initial search using only *Beauveria bassiana* returned 2,472 articles. This number was progressively reduced by applying the following keyword combinations: *Beauveria bassiana* AND crop (210 articles), *Beauveria bassiana* AND crop AND plant (101 articles), *Beauveria bassiana* AND crop AND plant AND mortality (42 articles), and finally *Beauveria bassiana* AND crop AND plant AND mortality AND entomopathogenic fungi (28 articles). After applying the publication date filter (2019-2024), 20 articles remained.

An identical search strategy was applied in PubMed, resulting in 30 articles. Duplicate entries between both databases and inaccessible full texts were excluded. A thorough review of the remaining articles was then performed, selecting only those that included pest mortality data, the concentration of *Beauveria bassiana* used during application, and the number of exposure days. Articles lacking any of these criteria were discarded, yielding a final selection of 24 articles for analysis (Figure 1). Studies that included comparisons between *B. bassiana* and other entomopathogenic fungi or chemical agents were also considered; however, only data specifically related to *B. bassiana* were extracted and analyzed in this review.

To generate graphical data, average pest mortality rates reported in the articles were used. This approach was chosen because some studies presented varying mortality outcomes across repeated trials; therefore, mean values were calculated to ensure consistency in the data analysis.

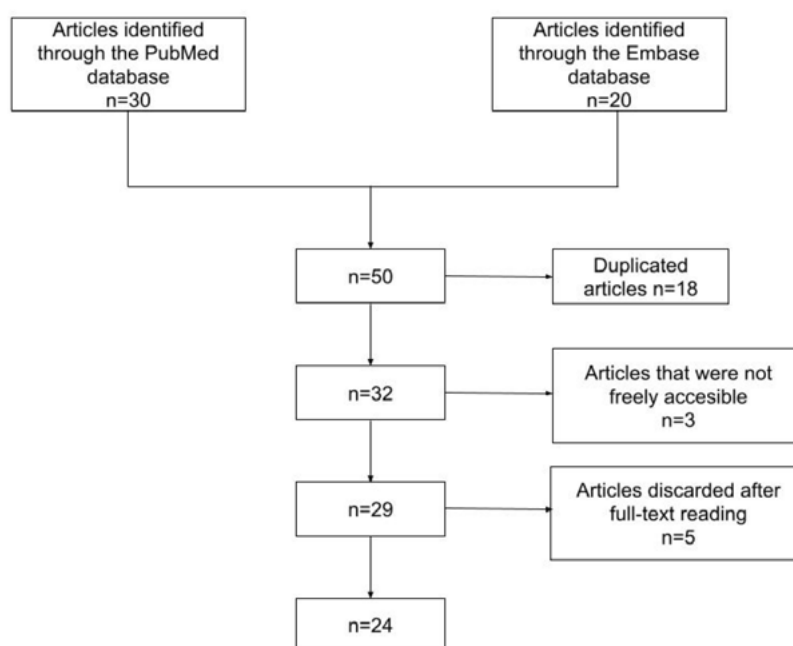


Figure 1. Flowchart for study identification.

RESULTS AND DISCUSSION

Through the review of 24 selected articles, various conidial concentrations of *Beauveria bassiana* used to assess pest mortality were analyzed. These concentrations ranged from $<1 \times 10^5$ to $>1 \times 10^{10}$ conidia/mL. A few studies reported extreme values, using concentrations as low as $<1 \times 10^2$ or as high as $>5 \times 10^{12}$ conidia/mL. However, these were excluded from the review as they served other purposes and did not report the required parameters (Figure 1). The reviewed studies demonstrated that *B. bassiana* can induce pest mortality at a range of concentrations (Figure 2). Nonetheless, the majority of the trials employed concentrations of 1×10^6 , 1×10^7 , 1×10^8 , and 1×10^9 conidia/mL, with 1×10^8 conidia/mL being the most frequently used. Notably, higher concentrations were typically associated with trials involving commercial formulations rather than locally sourced fungal isolates. This suggests that higher doses may be necessary to achieve effective results when using commercial strains, possibly due to their lower adaptability to local environmental conditions. In contrast, regionally adapted strains may exhibit better efficacy at lower concentrations, as they are more compatible with the local climate, soil, and target pests.

Regarding pest mortality data, considerable variability was observed in the relationship between reported mortality rates and the conidial concentrations used. This variability can be attributed to the type of pest targeted and the methodological differences among studies. Some experiments were conducted under laboratory conditions using seeds, culture media, plants, or directly on insects, while others were carried out in the field under diverse pest and crop scenarios.

Despite these differences, it was evident that concentrations of 1×10^6 and 1×10^8 conidia/mL were consistently associated with high mortality rates, whereas other concentrations tended to result in moderate or low mortality levels (Figure 3). Notably, in one study using a concentration $>1 \times 10^{10}$ conidia/mL, no significant increase in mortality was observed. This finding suggests that higher conidial concentrations do not necessarily correlate with

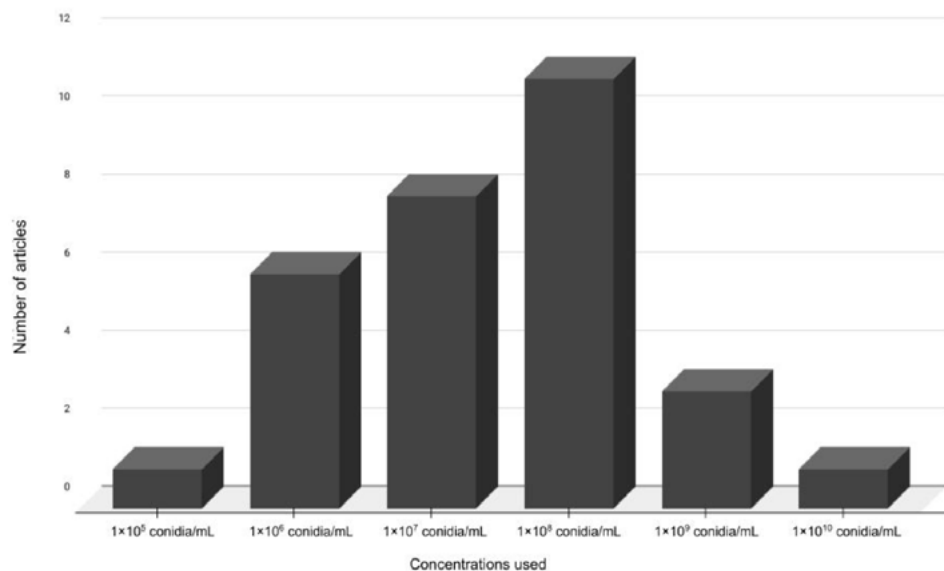


Figure 2. Comparison of *Beauveria bassiana* concentrations and pest mortality rates across studies.

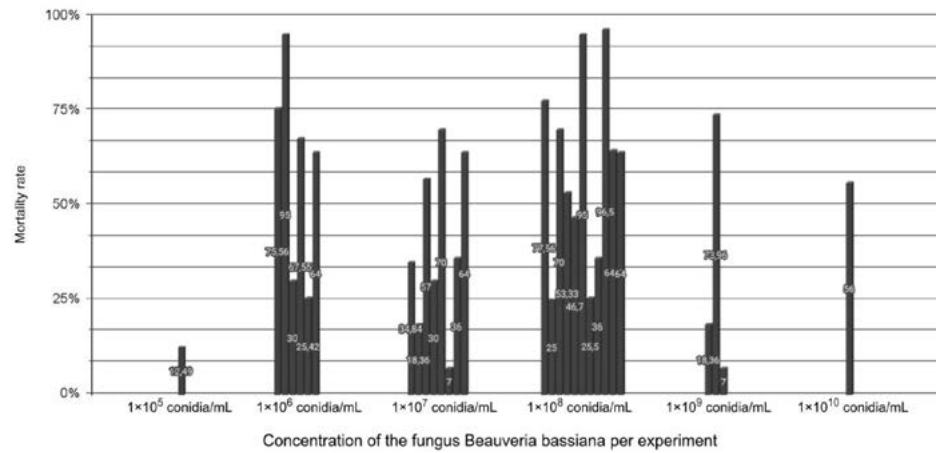


Figure 3. Average reported mortality rate by conidial concentration used in each study.

greater efficacy in pest control. However, it cannot be ruled out that the lack of effectiveness in this particular case may have been due to poor compatibility between *B. bassiana* and the specific pest species targeted.

Most of the analyzed studies were conducted on wheat, with several performed under laboratory conditions (Figure 4). Among the crops studied, higher pest mortality rates were reported in lemon, papaya, and tomato. However, due to the limited number of studies involving these specific crops, it is not possible to draw definitive conclusions regarding consistent mortality outcomes. Therefore, further research focused on these crops is necessary to allow for a more comprehensive and conclusive analysis.

According to the average mortality data reported in the analyzed studies (Figure 5), most recorded pest mortality rates ranging between 25% and 75%. Four studies reported mortality rates below 25%, while another four studies documented rates above 75%. These findings are consistent with prior research, which indicates that mortality rates generally range from 20% to 70%, depending on whether *B. bassiana* is applied to insect larvae or eggs (Ruiz Sánchez *et al.*, 2009).

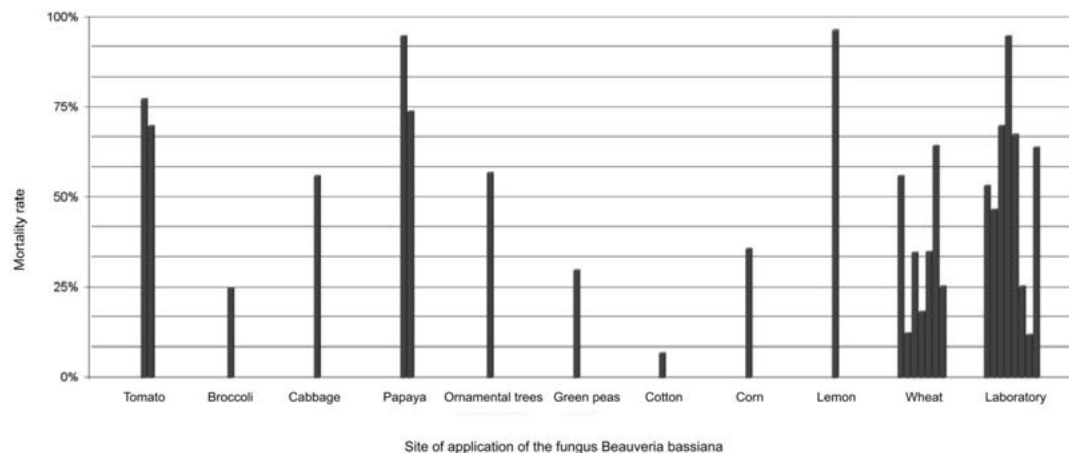


Figure 4. Average mortality reported in the reviewed studies following application of *Beauveria bassiana*.

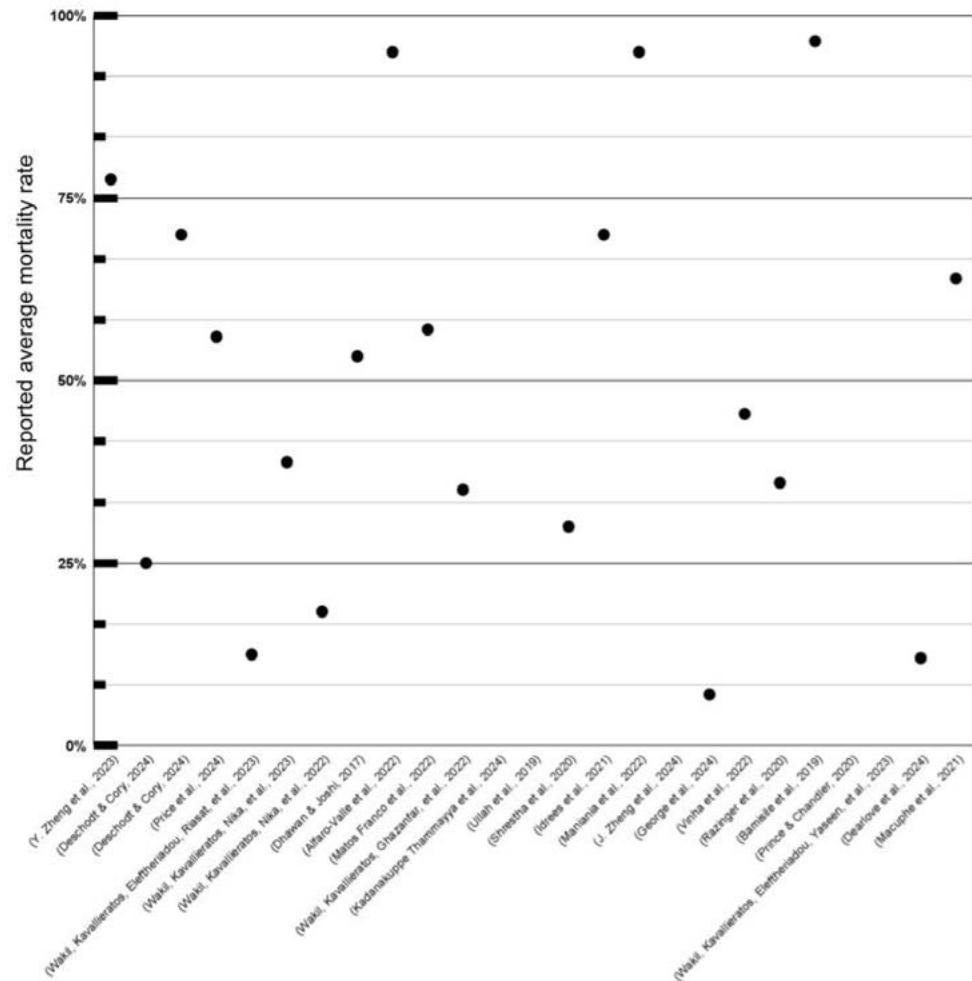


Figure 5. Average Mortality Percentage Reported in Each Analyzed Study.

Of the total articles reviewed, 23 focused on insecticidal activity and one reported acaricidal function (Figure 6). The latter achieved a 95% mortality rate against the papaya mite *Tetranychus merganser*, making *Beauveria bassiana* a promising option for mite control, as reported by Alfaro-Valle *et al.* (2022). The highest mortality rates were observed against a range of pest species, including *Phthorimaea absoluta* (Lepidoptera), *Tenebrio molitor* (Coleoptera), *Brevicoryne brassicae* (Hemiptera), *Diaphorina citri* Kuwayama (Hemiptera), *Lygus lineolaris* (Hemiptera), *Paracoccus marginatus* Williams & Granara de Willink (Hemiptera), *Phenacoccus solenopsis* Tinsley (Hemiptera), and the papaya mite *Tetranychus merganser*.

Based on the average mortality percentages reported across the reviewed studies, Coleopteran insects were the most frequently used organisms in experimental trials (Figure 7). However, mortality rates within this order varied considerably, ranging from 12.46% to 77.56%, making it difficult to establish a consistent expectation of *B. bassiana* efficacy against Coleoptera. In contrast, Hemipteran pests showed consistently high mortality rates. Eight out of nine studies reported mortality rates above 50%, with two

while its efficacy against Coleopterans and Lepidopterans appears to be more variable and less consistent. Consequently, the integration of *B. bassiana* with complementary pest management strategies is advised to enhance overall effectiveness.

Additionally, findings support the dual utility of *B. bassiana* as both an insecticide and acaricide, with one study reporting a 95% mortality rate against the mite *Tetranychus merganser*.

Finally, the optimal concentration for *B. bassiana* formulations, particularly when derived from local strains adapted to regional conditions, ranges between 1×10^7 and 1×10^8 conidia per milliliter.

ACKNOWLEDGEMENTS

The authors thank the University of Guadalajara and the Centro Universitario del Sur for their support.

REFERENCES

- Alfaro-Valle, E., Martínez-Hernández, A., Otero-Colina, G., & Lara-Reyna, J. (2022). High susceptibility of *Tetranychus merganser* (Acari: Tetranychidae), an emergent pest of the tropical crop *Carica papaya*, towards *Metarhizium anisopliae* s.l. and *Beauveria bassiana* strains. *PeerJ*, 10, e14064. <https://doi.org/10.7717/peerj.14064>
- Bamisile, B. S., Dash, C. K., Akutse, K. S., Qasim, M., Ramos Aguila, L. C., Wang, F., Keppanan, R., & Wang, L. (2019). Endophytic *Beauveria bassiana* in Foliar-Treated Citrus limon Plants Acting as a Growth Suppressor to Three Successive Generations of *Diaphorina citri* Kuwayama (Hemiptera: Liviidae). *Insects*, 10(6), 176. <https://doi.org/10.3390/insects10060176>
- Boedeker, W., Watts, M., Clausing, P., & Marquez, E. (2024). Retraction Note: The global distribution of acute unintentional pesticide poisoning: estimations based on a systematic review. *BMC Public Health*, 24(1), 2758. <https://doi.org/10.1186/s12889-024-20318-x>
- Dearlove, E. L., Chandler, D., Edgington, S., Berry, S. D., Martin, G., Svendsen, C., & Hesketh, H. (2024). Improved control of *Trialeurodes vaporariorum* using mixture combinations of entomopathogenic fungi and the chemical insecticide spiromesifen. *Scientific Reports*, 14(1), 15259. <https://doi.org/10.1038/s41598-024-66051-8>
- Deschodt, P. S., & Cory, J. S. (2024). Compatibility of the fungus *Beauveria bassiana* and *Trichoplusia ni* SNPV against the cabbage looper *Trichoplusia ni*: Crop plant matters. *Pest Management Science*, 80(6), 2851-2859. <https://doi.org/10.1002/ps.7993>
- Dhawan, M., & Joshi, N. (2017). Enzymatic comparison and mortality of *Beauveria bassiana* against cabbage caterpillar *Pieris brassicae* LINN. *Brazilian Journal of Microbiology: [Publication of the Brazilian Society for Microbiology]*, 48(3), 522-529. <https://doi.org/10.1016/j.bjm.2016.08.004>
- FAO. (2020). No hay seguridad alimentaria sin sanidad vegetal. Organización de las Naciones Unidas para la Alimentación y la Agricultura. <https://www.fao.org/>
- FAO. (2023). Versión resumida de El estado mundial de la agricultura y la alimentación 2023. <https://doi.org/10.4060/cc7937es>
- George, J., Glover, J. P., Perera, O. P., & Reddy, G. V. P. (2024). Role of Endophytic Entomopathogenic Fungi in Mediating Host Selection, Biology, Behavior, and Management of Tarnished Plant Bug, *Lygus lineolaris* (Hemiptera: Miridae). *Plants (Basel, Switzerland)*, 13(15), 2012. <https://doi.org/10.3390/plants13152012>
- González-Baca, G., Venegas Barrera, C. S., González Gaona, O. J., Vargas Madriz, H., Jiménez Gómez, M. A., Pérez Arriaga, E., Azuara Domínguez, A., González Baca, G., Venegas Barrera, C. S., González Gaona, O. J., Vargas Madriz, H., Jiménez Gómez, M. A., Pérez Arriaga, E., & Azuara Domínguez, A. (2019). Abundancia y distribución de hongos entomopatógenos en diferentes localidades y ambientes del sur de Tamaulipas. *Revista mexicana de ciencias agrícolas*, 10(3), 669-681. <https://doi.org/10.29312/remexca.v10i3.1550>
- Idrees, A., Qadir, Z. A., Akutse, K. S., Afzal, A., Hussain, M., Islam, W., Waqas, M. S., Bamisile, B. S., & Li, J. (2021). Effectiveness of Entomopathogenic Fungi on Immature Stages and Feeding Performance of Fall Armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae) Larvae. *Insects*, 12(11), 1044. <https://doi.org/10.3390/insects12111044>

- Kadanakuppe Thammayya, S., Manikyanahalli Chandrashekara, K., Chinapolaiah, A., Ramesan Syamala, R., Kadukothanahalli Veerabhadraiah, S., Somanna Gotyal, B., Channappa, M., Casini, R., Mohamed Moussa, I., Elansary, H. O., & El-Sabrou, A. M. (2024). Comparative effectiveness of biorational pesticides for management of *Phenacoccus solenopsis* Tinsley and *Paracoccus marginatus* Williams & Granara de Willink in *Gynmema sylvestre* (Retz.) R.Br. Ex Sm. *Heliyon*, *10*(1), e23648. <https://doi.org/10.1016/j.heliyon.2023.e23648>
- Lloclla Gonzales, H., Arellano Sánchez, C. W., Vásquez Vásquez, J. M., Maxe Malca, M. R., & García López, J. W. (2017). Patogenicidad de *Beauveria bassiana* (bals) vuill., sobre el gusano barrenador del loche *Diaphania hyalinata* (lepidoptera: Pyralidae) en laboratorio. UCV - HACER: *Revista de Investigación y Cultura*, *6*(2), 73-80.
- Macuphe, N., Oguntibeju, O. O., & Nchu, F. (2021). Evaluating the Endophytic Activities of *Beauveria bassiana* on the Physiology, Growth, and Antioxidant Activities of Extracts of Lettuce (*Lactuca sativa* L.). *Plants (Basel, Switzerland)*, *10*(6), 1178. <https://doi.org/10.3390/plants10061178>
- Malpartida-Zevallos, J., Narrea-Cango, M., & Dale-Larraburre, W. (2013). Patogenicidad de *Beauveria bassiana* (Bals) Vuill., sobre el gusano defoliador del maracuyá *Dione juno* (Cramer) (Lepidoptera: Nymphalidae) en laboratorio. *Ecología Aplicada*, *12*(2), 75-81.
- Maniania, N. K., Portilla, M. M., Amnulla, F. M., Mfuti, D. K., Darie, A., Dhiman, G., & Rao, I. M. (2022). Infectivity of Entomopathogenic Fungal Isolates Against Tarnished Plant Bug *Lygus lineolaris* (Hemiptera: Miridae). *Journal of Insect Science (Online)*, *22*(4), 4. <https://doi.org/10.1093/jisesa/ieac040>
- Matos Franco, G., Chen, Y., Doyle, V. P., Rehner, S. A., & Diaz, R. (2022). Will the application of biocontrol fungi disrupt predation of *Acanthococcus lagerstroemiae* by coccinellids? *Journal of Invertebrate Pathology*, *193*, 107789. <https://doi.org/10.1016/j.jip.2022.107789>
- Muñoz-Quezada, M. T., Lucero, B. A., Barr, D. B., Steenland, K., Levy, K., Ryan, P. B., Iglesias, V., Alvarado, S., Concha, C., Rojas, E., & Vega, C. (2013). Neurodevelopmental effects in children associated with exposure to organophosphate pesticides: A systematic review. *Neurotoxicology*, *39*, 158-168. <https://doi.org/10.1016/j.neuro.2013.09.003>
- Organización Panamericana de la Salud, Organización de las Naciones Unidas para la Alimentación y la Agricultura, (FAO), Programa de las Naciones Unidas para el Medio Ambiente (PNUMA) & Ministerio de Salud. (2014). Guía de diagnóstico y tratamiento de intoxicaciones agudas por plaguicidas. MSP. <http://repositorio.ministeriodesalud.gob.do/handle/123456789/197>
- Price, C. S. V., Campbell, H., & Pope, T. W. (2024). Assessing the potential of biopesticides to control the cabbage stem flea beetle *Psylliodes chrysocephala*. *Pest Management Science*, *80*(5), 2471-2479. <https://doi.org/10.1002/ps.7746>
- Prince, G., & Chandler, D. (2020). Susceptibility of *Myzus persicae*, *Brevicoryne brassicae* and *Nasonovia ribisnigri* to Fungal Biopesticides in Laboratory and Field Experiments. *Insects*, *11*(1), 55. <https://doi.org/10.3390/insects11010055>
- Razinger, J., Praprotnik, E., & Schroers, H.-J. (2020). Bioaugmentation of Entomopathogenic Fungi for Sustainable Agriotes Larvae (Wireworms) Management in Maize. *Frontiers in Plant Science*, *11*, 535005. <https://doi.org/10.3389/fpls.2020.535005>
- Ruiz Sánchez, E., Rosado Calderón, A. T., Chan Cupul, W., Alejo, J. C., & Munguía Rosales, R. (2009). Patogenicidad de *Beauveria bassiana* (Bals.) Vuillemin sobre estados inmaduros de mosquita blanca (*Bemisia tabaci* Genn.). *Fitosanidad*, *13*(2), 89-94.
- Shrestha, G., Mettupalli, S., Gadi, R., Miller, D. A., & Reddy, G. V. P. (2020). Spinosad and Mixtures of an Entomopathogenic Fungus and Pyrethrins for Control of *Sitona lineatus* (Coleoptera: Curculionidae) in Field Peas. *Journal of Economic Entomology*, *113*(2), 669-678. <https://doi.org/10.1093/jee/toz348>
- Silva, V., Mol, H. G. J., Zomer, P., Tienstra, M., Ritsema, C. J., & Geissen, V. (2019). Pesticide residues in European agricultural soils—A hidden reality unfolded. *The Science of the Total Environment*, *653*, 1532-1545. <https://doi.org/10.1016/j.scitotenv.2018.10.441>
- Ullah, M. I., Altaf, N., Afzal, M., Arshad, M., Mehmood, N., Riaz, M., Majeed, S., Ali, S., & Abdullah, A. (2019). Effects of Entomopathogenic Fungi on the Biology of *Spodoptera litura* (Lepidoptera: Noctuidae) and its Reduviid Predator, *Rhynocoris marginatus* (Heteroptera: Reduviidae). *International Journal of Insect Science*, *11*, 1179543319867116. <https://doi.org/10.1177/1179543319867116>
- UNICEF. (2022, marzo 1). Spotlight on risk: Pesticides. UNICEF. <https://ceh.unicef.org/spotlight-risk/pesticides>
- Vinha, F. B., Rojas, L. A. C., Ramos Sales, C., Monteiro Lima, N. S., Nascimento, J. D., De Carvalho, L. A. L., & Lemos, E. G. D. M. (2022). Negative effects on the development of *Chrysodeixis includens* and *Spodoptera cosmioides* fed by peanut plants inoculated with entomopathogenic fungi. *Frontiers in Fungal Biology*, *3*, 968528. <https://doi.org/10.3389/ffunb.2022.968528>

- Wakil, W., Kavallieratos, N. G., Eleftheriadou, N., Riasat, T., Ghazanfar, M. U., Rasool, K. G., Husain, M., & Aldawood, A. S. (2023). The Potential of Two Entomopathogenic Fungi and Enhanced Diatomaceous Earth Mixed with Abamectin: A Comprehensive Study on Mortality, Progeny Production, Application Method, and Surface Application against *Tribolium castaneum*. *Pathogens*, 12(6), 773. <https://doi.org/10.3390/pathogens12060773>
- Wakil, W., Kavallieratos, N. G., Eleftheriadou, N., Yaseen, T., Rasool, K. G., Husain, M., & Aldawood, A. S. (2023). Natural Warriors against Stored-Grain Pests: The Joint Action of *Beauveria bassiana* and *Steinernema carpocapsae*. *Journal of Fungi (Basel, Switzerland)*, 9(8), 835. <https://doi.org/10.3390/jof9080835>
- Wakil, W., Kavallieratos, N. G., Ghazanfar, M. U., & Usman, M. (2022). Laboratory and field studies on the combined application of *Beauveria bassiana* and fipronil against four major stored-product coleopteran insect pests. *Environmental Science and Pollution Research International*, 29(23), 34912-34929. <https://doi.org/10.1007/s11356-021-17527-x>
- Wakil, W., Kavallieratos, N. G., Nika, E. P., Ali, A., Yaseen, T., & Asrar, M. (2023). Two are better than one: The combinations of *Beauveria bassiana*, diatomaceous earth, and indoxacarb as effective wheat protectants. *Environmental Science and Pollution Research International*, 30(14), 41864-41877. <https://doi.org/10.1007/s11356-022-25075-1>
- Wakil, W., Kavallieratos, N., Nika, E., Qayyum, M., Yaseen, T., Ghazanfar, M., & Yasin, M. (2022). Combinations of *Beauveria bassiana* and spinetoram for the management of four important stored-product pests: Laboratory and field trials. *Environmental Science and Pollution Research*, 18. <https://doi.org/10.1007/s11356-022-23753-8>
- World Bank. (2024, marzo 15). Agricultura y alimentos. The World Bank Group. <https://www.bancomundial.org/es/topic/agriculture/overview>
- Zheng, J., Shi, J., & Wang, D. (2024). Diversity of soil fungi and entomopathogenic fungi in subtropical mountain forest in southwest China. *Environmental Microbiology Reports*, 16(4), e13267. <https://doi.org/10.1111/1758-2229.13267>
- Zheng, Y., Liu, Y., Zhang, J., Liu, X., Ju, Z., Shi, H., Mendoza-Mendoza, A., & Zhou, W. (2023). Dual role of endophytic entomopathogenic fungi: Induce plant growth and control tomato leafminer *Phthorimaea absoluta*. *Pest Management Science*, 79. <https://doi.org/10.1002/ps.7657>

Reduction in the incidence and recurrence of diarrhea in multibreed kids supplemented with *Bacillus subtilis* PB6 in Northern Mexico

Cervantes-Reyes, V.¹; Reboloso-Padilla, O.²; Carrillo-Moreno, D.I.¹; Contreras-Villarreal, V.¹; Ángel-García, O.¹; Rodríguez-Venegas, R.¹; De Santiago-Miramontes, M.A.^{1*}

¹ Universidad Autónoma Agraria Antonio Narro, Postgrado en Ciencias en Producción Agropecuaria, Torreón, Coahuila México. C. P. 27054.

² Universidad Autónoma Agraria Antonio Narro, Departamento de Producción Animal, Saltillo, Coahuila México. C. P. 25315.

* Correspondence: angelesdesantiago867@gmail.com

Citation: Cervantes-Reyes, V., Reboloso-Padilla, O., Carrillo-Moreno, D.I., Contreras-Villarreal, V., Ángel-García, O., Rodríguez-Venegas, R., & De Santiago-Miramontes, M.A. (2026). Reduction in the incidence and recurrence of diarrhea in multibreed kids supplemented with *Bacillus subtilis* PB6 in Northern Mexico. *Agro Productividad*. <https://doi.org/10.32854/ste81q45>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: November 28, 2025.

Accepted: January 14, 2026.

Published on-line: April XX, 2026.

Agro Productividad, 19(2). February, 2026. pp: 89-96.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



ABSTRACT

Objective: To evaluate the effect of probiotic supplementation (*Bacillus subtilis* PB6) on weight gain, as well as the incidence and recurrence of diarrhea and pneumonia in multibreed kids in northern Mexico.

Design/Methodology/Approach: The study was conducted in Ejido Corona, Municipality of Matamoros, Coahuila (northern Mexico). The experiment lasted 25 days in October 2022. Ninety-nine kids were randomly assigned to two homogeneous groups based on body weight (BW; 3.7 ± 0.2 kg). The control group (CG; n=50) received 5 mL of milk per kid per day. The treated group (TG; n=49) received 5 mL of milk per kid per day supplemented with 1 g/kg BW of *Bacillus subtilis* PB6. Administration was performed daily at 12:00 p.m. The probiotic dose was adjusted every five days, coinciding with body weight measurements.

Results: No significant difference was observed in final BW ($p > .05$; 7.7 ± 0.1 kg vs. 7.4 ± 0.2 kg for TG and CG, respectively). A significant difference was found in diarrhea incidence ($p < .05$; 28% vs. 50% for TG and CG, respectively), as well as in diarrhea recurrence ($p < .05$; 29% vs. 48% for TG and CG, respectively). These findings indicate that supplementation with *Bacillus subtilis* PB6 reduced the incidence and recurrence of diarrhea and may have contributed to the prevention of pneumonia.

Limitations/Implications: A longer supplementation period may be required to observe significant effects on body weight in kids.

Findings/Conclusions: Probiotic supplementation with *Bacillus subtilis* PB6 improved health outcomes by reducing diarrheal incidence and recurrence in multibreed kids raised under semi-arid conditions in northern Mexico.

Keywords: goats; intestinal health; probiotics; weight gain; diarrhea

INTRODUCTION

Semi-arid environments play a decisive role in the establishment of vegetation cover and the availability of forage resources, as they are characterized by low precipitation, high thermal variability, and vegetation dominated by natural grasslands and



xerophytic shrubs (Tarango, 2005; Sánchez *et al.*, 2023). Under these agroecological conditions, goat production has become established as a viable livestock activity due to the physiological adaptability of goats, their hardiness, and their ability to utilize low-quality forage.

In Mexico, goat production is concentrated primarily in the arid and semi-arid regions of the northern and central parts of the country, where annual precipitation ranges between 350 and 600 mm (FAO, 2011; Tarango, 2005). In these areas, extensive production systems predominate, based on daytime grazing and nighttime confinement, which helps reduce feeding costs by utilizing natural rangelands. Beyond its ecological suitability, goat production also plays a significant socioeconomic role, as it provides meat and milk that contribute to food security and income generation for small-scale rural producers (Echavarría *et al.*, 2006; Maldonado-Jáquez *et al.*, 2014).

Despite its productive importance, goat production in semi-arid regions faces significant constraints, particularly during the neonatal stage. Kid mortality represents one of the main factors affecting system profitability, resulting in considerable economic losses. Neonates possess an immature immune system, which increases their susceptibility to gastrointestinal and respiratory diseases (Cuéllar *et al.*, 2012). Among the primary causes of morbidity and mortality are infectious diarrheal diseases, whose etiological agents include *Escherichia coli*, *Salmonella* spp., *Clostridium perfringens*, coccidia of the genus *Eimeria*, and *Cryptosporidium* spp. (Alarcón-Aburto, 2005; Suárez *et al.*, 2007). Additionally, environmental factors such as low temperatures may increase the incidence of respiratory diseases, particularly pneumonia (Windeyer *et al.*, 2014; Cheng *et al.*, 2021).

Traditionally, antibiotics have been used for the prevention and treatment of these diseases; however, their indiscriminate use has raised concerns due to the development of antimicrobial resistance and the presence of residues in animal-derived products intended for human consumption. This scenario has prompted the search for sustainable alternatives that improve animal health without posing risks to public health. In this context, probiotics defined as live microorganisms that, when administered in adequate amounts, confer health benefits on the host (FAO/WHO, 2002) have emerged as a promising strategy in animal production. In ruminants, probiotic supplementation has been associated with improvements in intestinal health, feed efficiency, weight gain, and reduced incidence of diarrhea.

Nevertheless, information regarding the use of specific probiotic strains in kids raised under production systems in semi-arid regions remains limited. The strain *Bacillus subtilis* PB6 has demonstrated potential to maintain intestinal microbiota balance and improve productive performance in farm animals (Kritas & Morrison, 2005; Kritas *et al.*, 2006); however, its effects on the health and growth of neonatal kids have not been sufficiently documented. Therefore, the objective of the present study was to evaluate the effect of dietary supplementation with *Bacillus subtilis* PB6 on weight gain, as well as on the incidence and recurrence of diarrhea and pneumonia in multibreed kids raised under semi-arid conditions in northeastern Mexico.

MATERIALS AND METHODS

All methods and management of the experimental groups were conducted in accordance with international (ASAS, 2020) and national (NAM, 2002) guidelines for the care, ethical use, and welfare of research animals, with institutional approval (UAAAN-UL: 3811-425502002-2792).

Description of location and environmental conditions

The study was conducted in the municipality of Matamoros, Coahuila, a semi-arid region in northeastern Mexico (103°15' 38" W, 25° 35' 03" N; 1,111 m) (INEGI, 2020). The mean annual precipitation is 230 mm, with an average annual temperature of 22 °C, a maximum of 38 °C, and a minimum of 8 °C (CONAGUA, 2018).

Animals and treatments

Ninety-nine kids were randomly selected and assigned to two homogeneous groups based on birth weight: Treatment Group (TG; n=49; 3.8 kg body weight [BW]) and Control Group (CG; n=50; 3.7 kg BW). Colostrum intake was ensured through direct suckling.

During part of the lactation period (25 days), from October 7 to November 1, 2022, both groups received 5 mL of milk per kid administered orally using a disposable syringe. The milk provided to the TG was supplemented with 1 g of a commercial product containing 2×10^8 colony-forming units (CFU) of *Bacillus subtilis* PB6 per kilogram of body weight. Administration was performed daily at 12:00 p.m. The probiotic dose was adjusted according to BW every five days, coinciding with the weighing of the kids.

Evaluated variables

Body weight

Body weight was recorded using a digital hanging scale (WH-100) at the beginning of the study and every five days over a 25-day period.

Incidence and recurrence of diarrhea

Each kid was monitored daily through observation of feces in the perianal area. When diarrhea was detected, a small sample was collected and transported to the pathology laboratory at UAAAN, where fecal color (dark green, white, or orange) was recorded. Diagnosis was performed using coprological examinations and Ziehl-Neelsen staining to determine the etiological agent of the diarrhea. Additionally, each kid was examined daily for clinical signs of pneumonia. Disease incidence was determined by recording the number of confirmed cases, and recurrence was defined as the number of cases that resolved and subsequently reoccurred within the 25-day study period.

Statistical analysis

To determine differences in weight gain between groups was performed using the Student's t test. Differences in the proportions of kids with incidence and recurrence of diarrhea and pneumonia were evaluated using the chi-square test. A significance level

of $p < .05$ was established to determine statistical differences. Statistical analyses were conducted using SYSTAT version 12. Incidence was defined as the number of new cases occurring within a specified period divided by the population at risk ($I = \text{amount of cases} / \text{population at risk}$). Recurrence was defined as the number of existing cases within a population at a given time, without distinguishing between new and previous cases (WHO & PAHO, 2018).

RESULTS AND DISCUSSION

For the final body weight variable (25 days of age), no significant difference was observed ($p > .05$; 7.7 ± 0.1 kg *vs.* 7.4 ± 0.2 kg) between the TG and CG, respectively (Table 1).

Incidence of diarrhea

Laboratory diagnosis identified *Cryptosporidium parvum* as the etiological agent responsible for the diarrheal cases observed, infecting the intestinal tract of the kids. The incidence of diarrhea was higher in the control group than in the treated group ($p < .05$; 50% *vs.* 28%). Likewise, a significant difference was observed in the recurrence of diarrhea (48% *vs.* 29%), favoring the TG (Table 2).

Regarding pneumonia, only one kid death was recorded with an initial suspicion of this condition (control group). However, postmortem examination revealed that the cause of death was drowning due to animal overcrowding during the night.

In the present study, greater weight gain (kg) was hypothesized in the TG, along with lower incidence and recurrence of diarrhea and pneumonia. The results showed no statistically significant difference in body weight between groups. This finding is consistent with Souza *et al.* (2021), who administered *Bacillus subtilis* PB6 in poultry, cows, and deer and reported no significant weight gain. Similarly, studies evaluating weight gain in kids have reported significant differences only after 30 days of supplementation (Sivadasan, 2020). However, in our study, a significant difference was observed in diarrhea incidence.

Table 1. Body weight (kg) of two groups of multibreed kids from northeastern Mexico supplemented with *Bacillus subtilis* PB6 for 25 days after birth.

Body weight (kg)	TG (n=49)	CG (n=50)
Initial	3.8 ± 0.1^a	3.7 ± 0.2^a
Final	7.7 ± 0.1^a	7.4 ± 0.2^a

^{a, b} Means within rows do not differ significantly ($p > .05$).

Table 2. Incidence and recurrence of diarrhea and pneumonia in multibreed kids from northeastern Mexico supplemented with *Bacillus subtilis* PB6 for 25 days after birth.

Diarrhea	GT (n=49)	GC (n=50)
Diarrhea incidence, n (%)	14/49 (28) ^a	25/50 (50) ^a
Diarrhea recurrence, n (%)	4/14 (29) ^a	12/25 (48) ^a
Pneumonia, n (%)	0/49 (0) ^a	1/50 (2) ^a

^{a, b} Means within rows do not differ significantly ($p > .05$).

The control group presented 25 cases (50%) of diarrhea, compared with only 14 cases (28%) in the probiotic-treated group. Likewise, recurrence of this condition was lower in the TG than in the CG (29% *vs.* 48%). These findings are consistent with studies evaluating probiotic supplementation in goats, which reported a reduction in diarrhea cases (Galina & Puga, 2009).

Microbial populations in the digestive system of animals are highly specialized and composed of diverse microorganisms, including bacteria, fungi, and protozoa (Figuroa & Vilades, 2008). These microorganisms are responsible for essential digestive and fermentative functions, such as vitamin synthesis, maintenance of intestinal mucosal integrity, and protection against pathogenic agents (Relling & Mattioli, 2003). Based on this premise, the findings of the present study may be interpreted in light of the lower incidence of diarrhea observed in the treated group compared with the control group. This reduction may be attributed to the inhibitory effects of probiotics on pathogenic agents, thereby decreasing the occurrence of the disease.

Studies evaluating probiotics in animals have demonstrated that their beneficial effects are associated with specific mechanisms of action. Probiotic strains can positively influence digestive system balance by adhering to the intestinal epithelium and exerting competitive exclusion, bacterial antagonism, and immunomodulatory effects. These mechanisms are reflected in reduced populations of pathogenic bacteria and improved nutrient utilization (Markowiak & Ślizewska, 2018).

Probiotic supplementation in goats has been shown to improve intestinal health and support disease prevention by reducing pathogenic bacterial strains that affect the gastrointestinal tract, thereby decreasing disease incidence. Studies in sheep supplemented with *Bacillus subtilis* have reported improvements in intestinal health, productivity, metabolic profile, and reduced disease occurrence (Devyatkin, Mishurov, & Kolodina, 2021; Sheikh *et al.*, 2022).

The favorable results obtained in the present study regarding intestinal health may be attributed to the ability of probiotics to produce bacteriocins, adhere to the intestinal epithelium, and modify pH levels. These mechanisms create unfavorable conditions for pathogenic microorganisms, thereby limiting their survival and contributing to a reduction in disease occurrence (Corr *et al.*, 2007; Shim *et al.*, 2012; Jordan *et al.*, 2014).

Previous research has reported a reduction in pathogenic strains (*Escherichia coli*, *Clostridium* spp., and *Salmonella* spp.) in various animal species, including poultry and piglets, following probiotic supplementation. These studies have also documented an increase in populations of *Lactobacillus* and *Bifidobacterium*, resulting in improvements in gut microbiota composition, enhanced digestive health, reduced incidence of diarrhea, and improved nutritional status (Shim *et al.*, 2012; Liu *et al.*, 2014; Mookiah *et al.*, 2014; Zhang & Kim, 2014; Zhang *et al.*, 2016). Other studies have reported that supplementation with lactic acid bacteria and *Bacillus* spp. modifies microbial populations within the gastrointestinal tract (Abdelqader, Irshaid, & Al-Fataftah, 2013). Additionally, probiotic supplementation has been shown to improve intestinal health, enhance milk quality, support disease prevention, and promote weight gain after 30 days of supplementation (Abd El-Tawab *et al.*, 2016).

Although no cases of pneumonia were recorded in the present study, this absence may be attributed to the environmental conditions of the study area, as well as to the lack of coccidiosis cases, which have been associated with increased pneumonia incidence (Donkin & Boyazoglu, 2004; Kattimani *et al.*, 2020). Given the limited number of studies evaluating weight gain in kids supplemented with probiotics, it is possible that supplementation periods longer than 30 days are required to observe measurable effects on body weight.

CONCLUSIONS

Supplementation with *Bacillus subtilis* PB6 improved the health status of the kids and reduced both the incidence and recurrence of diarrhea. Additionally, it may have contributed to the prevention of pneumonia. A longer supplementation period with *Bacillus subtilis* PB6 may enhance body weight in multibreed kids raised in northern Mexico.

REFERENCES

- Abd El-Tawab MM, Youssef IM, Bakr HA, Fthenakis GC, Giadinis ND. Role of probiotics in nutrition and health of small ruminants. (2016). *Polish Journal of Veterinary Sciences*. 19(4):893-906. doi: 10.1515/pjvs-2016-0114. PMID: 28092597.
- Abdelqader, A., Irshaid, R. & Al-Fataftah, AR. (2013). Effects of dietary probiotic inclusion on performance, eggshell quality, cecal microflora composition, and tibia traits of laying hens in the late phase of production. *Tropical animal health and production*, 45, 1017-1024. <https://doi.org/10.1007/s11250-012-0326-7>
- Alarcon Aburto, A. (2005) 'Problemas de Diarreas en Cabritos', pp. 1-15. Available at: [http://amaltea.fmvz.unam.mx/textos/Diarreas en cabritos PAPIME.pdf](http://amaltea.fmvz.unam.mx/textos/Diarreas%20en%20cabritos/PAPIME.pdf).
- Cheng, Y., Yang, C., Tan, Z., & He, Z. (2021). Changes of Intestinal Oxidative Stress, Inflammation, and Gene Expression in Neonatal Diarrhoea Kids. *Frontiers in Veterinary Science*, 8:598691. doi: 10.3389/fvets.2021.598691
- Chopra, K., Dua, N. and Saha, K. (1986). The role of colostrum. In: Diarrhoea and Malnutrition in Childhood, J.A. Walker-Smith, A.S. McNeishpp (Eds). Butterworth-Heinemann, Elsevier BV. Pp: 229-232. <https://doi.org/10.1016/b978-0-407-00401-6.50042-7>
- Corr, S.C. et al. (2007) 'Bacteriocin production as a mechanism for the anti-infective activity of *Lactobacillus salivarius* UCC118', *Proceedings of the National Academy of Sciences of the United States of America*, 104(18), pp. 7617-7621. Available at: <https://doi.org/10.1073/pnas.0700440104>.
- Cuellar, O.J.A. *et al.* (2012) 'La producción caprina mexicana, particularidades y complejidades', Ed. Aridana, México, DF [Preprint].
- Devyatkin, V., Mishurov, A. and Kolodina, E. (2021) 'Probiotic effect of *Bacillus subtilis* B-2998D, B-3057D, and *Bacillus licheniformis* B-2999D complex on sheep and lambs', *Journal of Advanced Veterinary and Animal Research*, 8(1), pp. 146-157. Available at: <https://doi.org/10.5455/javar.2021.h497>.
- Donkin, E.F. and Boyazoglu, P.A. (2004) 'Diseases and mortality of adult goats in a South African milk goat herd', *South African Journal of Animal Science*, 34(SUPPL. 1), pp. 254-257.
- Echavarría Cháirez, F. G., Serna Pérez, A., & Bañuelos Valenzuela, R. (2012). Influencia del sistema de pastoreo con pequeños rumiantes en un agostadero del semiárido zacatecano: II. Cambios en el suelo. *Revista Mexicana De Ciencias Pecuarias*, 45(2): 177-194. Recuperado a partir de <https://cienciaspecuarias.inifap.gob.mx/index.php/Pecuarias/article/view/1777>
- Echavarría, C. F.G., Gutiérrez Luna, R., Ledesma Rivera, R.I., Bañuelos Valenzuela, R., Aguilera Soto, J.I., Serna Pérez, A. (2006). Influencia del sistema de pastoreo con pequeños rumiantes en un agostadero del semiárido Zacatecano. I Vegetación nativa, *Técnica Pecuaria en México*, 44(2):203-217. <https://cienciaspecuarias.inifap.gob.mx/index.php/Pecuarias/article/view/1748/1742>
- Echavarría, FG. Gutiérrez, RL. Ledesma, RI. Bañuelos, RV. Aguilera, JI. Serna, A. (2006) 'Influencia del sistema de pastoreo con pequeños rumiantes en un agostadero del semiárido Zacatecano. I Vegetación nativa', *Tec Pecu Méx*, 44(2), pp. 203-217.
- Essa MOA, Cheng C, Li J, Han X, Wei ZK, Abdelhadi LAM, Hassan HA, Adam SY, Husien HM, Saleh AA and Cheng D (2025) Probiotic administration correlated with reduced diarrheal incidence and improved gut microbiota diversity in young goats. *Front. Vet. Sci.* 12:1604638. doi: 10.3389/fvets.2025.1604638

- Figuroa Valenzuela, C., Meda Gutiérrez, F.J. and Janacua Vilades, H. (2008) 'Manual de buenas prácticas en producción de leche caprina', p. 68.
- Galina, M.A. and Puga, L.J.P.D.C. (2009) 'Cinética ruminal y crecimiento de cabritos suplementados con un probiótico de bacterias ácido-lácticas *Ruminal kinetics and growth of kids supplemented with a lactic acid bacteria probiotic*', 32(4), pp. 395-405.
- Jaime Sánchez¹, Eduardo Estrada Castillón², Mario A. García Aranda^{1,3}, Mario F. Duarte Hernández¹, Fabián García González⁴, Luis M. Valenzuela Nuñez¹, Gisela Muro Pérez¹. (2023). Arid and semi-arid environments: their relationship with the dispersion and germination of species. *Revista Mexicana de Ciencias Forestales*, 14(75):35-67. DOI: 10.29298/rmcf.v14i75.1288
- Jordan, K. et al. (2014) 'Microbes versus microbes: control of pathogens in the food chain', *Journal of the Science of Food and Agriculture*, 94(15), pp. 3079-3089. Available at: <https://doi.org/https://doi.org/10.1002/jsfa.6735>.
- Kattimani, T.S. et al. (2020) 'Prevalence of pneumonia in goats in and around the Bidar', ~ 250 ~ *The Pharma Innovation Journal*, 9(1), pp. 250-252. Available at: <http://www.thepharmajournal.com>.
- Kritas, S.K. and Morrison, R.B. (2005) 'Evaluation of probiotics as a substitute for antibiotics in a large pig nursery.', *The Veterinary record*, 156(14), pp. 447-448. Available at: <https://doi.org/10.1136/vr.156.14.447>.
- Kritas, S.K. et al. (2006) 'Effect of *Bacillus licheniformis* and *Bacillus subtilis* supplementation of ewe's feed on sheep milk production and young lamb mortality', *Journal of Veterinary Medicine Series A: Physiology Pathology Clinical Medicine*, 53(4), pp. 170-173. Available at: <https://doi.org/10.1111/j.1439-0442.2006.00815.x>.
- Liu, H. et al. (2014) 'Oral administration of *Lactobacillus fermentum* I5007 favors intestinal development and alters the intestinal microbiota in formula-fed piglets.', *Journal of agricultural and food chemistry*, 62(4), pp. 860-866. Available at: <https://doi.org/10.1021/jf403288r>.
- Lu Christopher D. Miller Beth A. (2019) 'Current status, challenges and prospects for dairy goat production in the Americas', *Asian-Australas J Anim Sci*, 32(8), pp. 1244-1255. Available at: <https://doi.org/10.5713/ajas.19.0256>.
- Macpherson, A.J. and Harris, N.L. (2004) 'Interactions between commensal intestinal bacteria and the immune system.', *Nature reviews. Immunology*, 4(6), pp. 478-485. Available at: <https://doi.org/10.1038/nri1373>.
- Markowiak, P. and Ślizewska, K. (2018) 'The role of probiotics, prebiotics and synbiotics in animal nutrition', *Gut Pathogens*, 10(1), pp. 1-20. Available at: <https://doi.org/10.1186/s13099-018-0250-0>.
- Mookiah, S. et al. (2014) 'Effects of dietary prebiotics, probiotic and synbiotics on performance, caecal bacterial populations and caecal fermentation concentrations of broiler chickens.', *Journal of the science of food and agriculture*, 94(2), pp. 341-348. Available at: <https://doi.org/10.1002/jsfa.6365>.
- Mugoti, A., Nyamukanza, C., Munengwa, A., Moyo, S. and Chikumba, N. (2025). Effects of climate change on goat production and mitigatory measures in semiarid savanna ecosystems. *JOURNAL OF INTEGRATIVE ENVIRONMENTAL SCIENCES*, 22(1): 2513899. <https://doi.org/10.1080/1943815X.2025.2513899>
- Relling, A.E. and Mattioli, G.A.. (2003) 'Fisiología digestiva y metabólica de los rumiantes', *EduLP*, pp. 1-72.
- Salud, O.P. de la and Salud, O.P. de la (2018) 'Indicadores de salud. Aspectos conceptuales y operativos'. Available at: <https://doi.org/https://doi.org/10.37774/9789275320051 PP - Washington, D.C>.
- Sentíes-Herrera, H.E., Trejo-Téllez, L.I., Volke-Haller, V.H., Cadena-Íñiguez, J., Sánchez-García, P., & Gómez-Merino, F.C. (2018). Iodine, silicon, and vanadium differentially affect growth, flowering, and quality components of stalks in sugarcane. *Sugar Tech* 20: 518-533. doi: 10.1007/s12355-017-0572-0
- Sheikh, G.G. et al. (2022) 'Rumen microflora, fermentation pattern and microbial enzyme activity in sheep fed paddy straw based complete feed fortified with probiotics', *Biological Rhythm Research*, 53(4), pp. 547-558. Available at: <https://doi.org/10.1080/09291016.2019.1644019>.
- Shi, H.N. and Walker, A. (2004) 'Bacterial Colonization and the Development of Intestinal Defences', *Canadian Journal of Gastroenterology*, 18, p. 690421. Available at: <https://doi.org/10.1155/2004/690421>.
- Shim, Y.H. et al. (2012) 'A multi-microbe probiotic formulation processed at low and high drying temperatures: effects on growth performance, nutrient retention and caecal microbiology of broilers.', *British poultry science*, 53(4), pp. 482-490. Available at: <https://doi.org/10.1080/00071668.2012.690508>.
- Sivadasan, K.S. (2020) 'Comparison of Growth Performance of Goat Kids Under Supplementation with Different Probiotics', *Journal of Animal Research*, 10(6), pp. 1063-1065. Available at: <https://doi.org/10.30954/2277-940x.06.2020.28>.
- Souza, O. et al. (2021) 'The Impact of *Bacillus subtilis* PB6 and Chromium Propionate on the Performance, Egg Quality and Nutrient Metabolizability of Layer Breeders', *ANIMALS*, 11(11). Available at: <https://doi.org/10.3390/ani11113084>.
- Suarez, V. et al. (2007) 'Enfermedades parasitarias de los ovinos y otros rumiantes menores en el cono sur de América.' Available at: <https://doi.org/10.13140/RG.2.1.5061.5280>.

- Tarango, A. L. A. (2005). Problemática y alternativas de desarrollo de las zonas áridas y semiáridas de México. *Revista Chapingo Serie Zonas Áridas*, IV(2): pp. 17-21. Disponible en: <https://www.redalyc.org/articulo.oa?id=455545052003>
- Turner, J. (1972). Freedom to build, dweller control of the housing process. New York: Macmillan.
- Wang, P., Zhang, Y., Zhao, L., Mo, B., & Luo, T. (2017). Effect of gamma rays on *Sophora davidii* and detection of DNA polymorphism through ISSR marker. *BioMed Research International* 2017, Article ID 8576404. doi: 10.1155/2017/8576404
- Windeyer, M.C. et al. (2014) 'Factors associated with morbidity, mortality, and growth of dairy heifer calves up to 3 months of age.', *Preventive veterinary medicine*, 113(2), pp. 231-240. Available at: <https://doi.org/10.1016/j.prevetmed.2013.10.019>.
- Zhang, Ling et al. (2016) 'Effects of dietary supplementation of probiotic, *Clostridium butyricum*, on growth performance, immune response, intestinal barrier function, and digestive enzyme activity in broiler chickens challenged with *Escherichia coli* K88.', *Journal of animal science and biotechnology*, 7, p. 3. Available at: <https://doi.org/10.1186/s40104-016-0061-4>.
- Zhang, Z.F. and Kim, I.H. (2014) 'Effects of multistrain probiotics on growth performance, apparent ileal nutrient digestibility, blood characteristics, cecal microbial shedding, and excreta odor contents in broilers.', *Poultry science*, 93(2), pp. 364-370. Available at: <https://doi.org/10.3382/ps.2013-03314>.

Rooting of Tomato Cuttings in Nutrient Solution or Substrate: An Alternative for High-Density Production Systems

Sánchez-Del Castillo, Felipe¹, Mejía-Betancourt, Francisca de los Ángeles²,
Moreno-Pérez, Esaú del Carmen^{1*}, González-Molina, Lucila³

¹ Universidad Autónoma Chapingo. Texcoco, Estado de México, México. C. P. 56230.

² Universidad Nacional Agraria. Managua, Nicaragua. C. P. 453.

³ Campo Experimental Valle de México-INIFAP. Texcoco, Estado de México, México. C. P. 56250.

* Correspondence: esaump10@yahoo.com.mx

ABSTRACT

Objective: To evaluate the quality of tomato seedlings produced from cuttings rooted in a nutrient solution and in solid substrates (peat moss, red volcanic rock, and a mixture of both substrates), and to determine their subsequent effects on plant growth and yield.

Design/methodology/approach: Cuttings were collected from 80-day-old mother plants. After treatments were established, rooting was conducted inside a controlled structure maintained at 15-20 °C and 70% relative humidity (RH). Irrigation was applied automatically every hour for two minutes using a nutrient solution at 50% strength. The experimental design was a randomized complete block design (RCBD) with four replications. Growth variables were recorded 20 days after rooting initiation and at the onset of harvest. Subsequently, yield and its components were assessed.

Results: All seedlings met quality standards at transplanting; however, seedlings derived from cuttings rooted in nutrient solution exhibited significantly greater stem diameter (7.3 mm), leaf area (354.5 cm²), and dry weight (3.1 g). Nonetheless, at the adult plant stage, no differences in growth or yield were detected among treatments.

Limitations on study/implications: An economic feasibility analysis is required for each substrate evaluated.

Findings/conclusions: For seedling production, rooting in nutrient solution or in a 1:1 (v/v) mixture of peat moss and red volcanic rock constitutes a more viable option in terms of cost-effectiveness and accessibility.

Keywords: Tomato cuttings, nutrient solution, substrates, seedling quality.

Citation: Sánchez-Del Castillo, F., Mejía-Betancourt, F. de los Á., Moreno-Pérez, E. del C., & González-Molina, L. (2026). Rooting of Tomato Cuttings in Nutrient Solution or Substrate: An Alternative for High-Density Production Systems. *Agro Productividad*. <https://doi.org/10.32854/6ftdea19>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: June 6, 2024.

Accepted: January 3, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 97-105.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is the most widely cultivated horticultural species under protected cultivation in Mexico (SIAP, 2023; USDA, 2024). Within tomato production systems, the nursery stage is particularly critical, because seedling quality directly determines the number of flowers and fruits set in the first trusses (Gaytán-Ruelas



et al., 2016; Moreno-Pérez *et al.*, 2021). The cost of seedlings destined for greenhouse management is high, primarily because hybrid seeds and relatively expensive substrates are typically used for sowing (Moreno *et al.*, 2021; Mejía *et al.*, 2023). In Mexico, the substrate most commonly used for tray-based seedling production is sphagnum peat moss, either alone or combined with perlite. Both materials exhibit physical and chemical properties that promote optimal seedling growth due to their high capacity for water retention and root-zone oxygen availability (Lazcano-Bello *et al.*, 2021). Nevertheless, both substrates are costly (Ortega-Martínez *et al.*, 2010), a constraint that becomes even more pronounced in production systems operating at high plant densities, as proposed by Sánchez-Del Castillo *et al.* (2010), Sánchez-Del Castillo *et al.* (2012), and Moreno-Pérez *et al.* (2021). In such systems, up to 80,000 plants ha⁻¹ may be established in a four-month crop cycle, and as many as 240,000 seedlings ha⁻¹ year⁻¹ when three crop cycles per year are implemented. Accordingly, the present study proposes the use of rooted cuttings as a substitute for conventional botanical seed propagation (Moreno-Pérez *et al.*, 2016; Mejía-Betancourt *et al.*, 2023), together with the use of low-cost media such as tezontle sand (red volcanic rock) for rooting and/or transplant production, or even the use of a nutrient solution as a rooting medium in place of the high-cost substrates commonly employed (Ortega-Martínez *et al.*, 2010; Moreno-Pérez *et al.*, 2016; Cheiri *et al.*, 2018; Urrestarazu-Gavilán, 2023). Based on this rationale, the objective of this work was to evaluate the quality of tomato seedlings obtained from cuttings rooted in different solid substrates or in a nutrient solution, and to determine their effects on plant growth and yield at the end of the cropping cycle. The hypothesis is that seedlings produced from cuttings rooted in nutrient solution will exhibit high transplant quality and comparable if not superior productive performance relative to those rooted in substrate, given that immediate nutrient availability in solution may optimize development while reducing production costs. In addition, it is proposed that combining fine tezontle sand with peat moss may be ideal for rooting cuttings, because tezontle provides high moisture retention, whereas peat moss enhances root-zone aeration.

MATERIALS AND METHODS

Site and biological material

The nursery phase was conducted in a 300 m² greenhouse located at the Experimental Field of the Universidad Autónoma Chapingo. This greenhouse was equipped with a high light-diffusion thermal polyethylene cover, anti-aphid insect-proof screens, and a climate-control system consisting of heating, a wet wall, and exhaust fans to regulate temperature and relative humidity. Subsequent crop management was performed in a separate 500 m² greenhouse with characteristics similar to those of the nursery facility. The tomato hybrid 'Pai Pai' (Enza Zaden), a saladette-type cultivar with an indeterminate growth habit, high yield potential, and broad adoption among growers, was used.

Experimental design and treatments

A randomized complete block design (RCBD) was implemented with four treatments and four replications, using 10 plants per experimental unit. The treatments (Figure 1) were as follows:

Treatment 1: Rooting of cuttings in nutrient solution. A plastic tray (25 cm wide × 50 cm long × 20 cm deep) was filled with a 50% strength nutrient solution containing the following nutrients (mg L^{-1}): N=200, P=50, K=250, Ca=300, S=150, Mg=50, Fe=2, Mn=1, Cu=1, Mo=0.5, B=0.5, and Zn=0.5. A perforated polystyrene (Styrofoam) sheet with holes spaced 10 cm apart in both directions was placed over the tray, and tomato shoots were inserted into the holes for rooting.

Treatment 2 (control): Rooting of cuttings in 60-cell trays (200 cm^3 per cell) filled with peat moss as the substrate.

Treatment 3: Rooting of cuttings in 60-cell trays (200 cm^3 per cell) filled with fine red tezontle (red volcanic rock) sand (particle size 1-3 mm in diameter).

Treatment 4: Rooting of cuttings in 60-cell trays filled with a 1:1 (v/v) mixture of fine tezontle sand and peat moss.

Variables evaluated

At 20 days after cutting rooting, seedlings were assessed for: plant height (cm), measured from the root collar to the apical shoot; stem diameter (mm), measured between the second and third leaves; leaf area (cm^2), using a LI-3000A leaf area meter (LI-COR, Lincoln, Nebraska); root volume (cm^3), determined by the water-displacement method in a graduated cylinder; and dry weight (g), obtained by oven-drying seedlings at $70 \text{ }^\circ\text{C}$ for three days.

At the onset of harvest (90 days after transplanting), plants were evaluated for: plant height (cm), measured from the root collar to the terminal topping point; stem diameter (mm), measured below the second basal leaf; plant width (cm), recorded at the widest point without manually extending the leaves; and leaf area index (LAI), calculated by multiplying the leaf area per plant by the plant density (plants m^{-2}) in the greenhouse, using a LI-3000A leaf area meter (LI-COR, Lincoln, Nebraska). In addition, the number of flowers and fruits per plant, mean fruit weight (g), and yield per plant (kg plant^{-1}) were determined.



Figure 1. Treatments evaluated: (a) T1 (rooting of cuttings in nutrient solution), (b) T2 (rooting of cuttings in peat moss), (c) T3 (rooting of cuttings in fine red tezontle [red volcanic rock]), and (d) T4 (rooting of cuttings in a mixture of peat moss + fine red tezontle).

Experimental management

For the rooting of tomato cuttings (shoots), the methodology described by Mejía-Betancourt *et al.* (2023) was followed, with the following adaptations:

- a) Shoots were collected from 80-day-old mother plants (Figure 2).
- b) Inside a greenhouse, a structure measuring 10 m long \times 3 m wide \times 2.5 m high was constructed using agribon mesh and smooth galvanized wire. The structure was equipped with a water tank containing nutrient solution, a pump, piping, low-pressure misting nozzles, and metal stands to support the trays (Figure 3). Misting nozzles were installed at 1.3 m intervals to deliver irrigation (50% strength nutrient solution) to cuttings during rooting, applied every 2 h for 2 min. Internal temperature was maintained between 15 and 20 °C, and relative humidity (RH) between 70 and 80%.

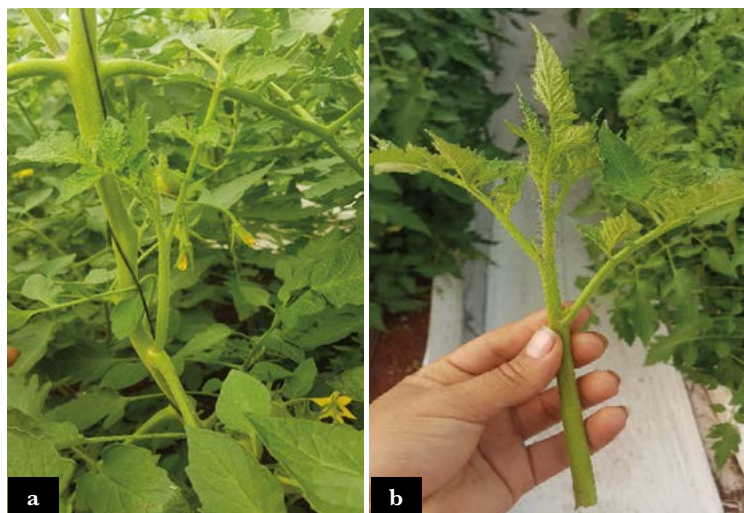


Figure 2. Collection of a lateral shoot with the ideal characteristics for rooting: (a) mother plant and (b) shoot selected for rooting.

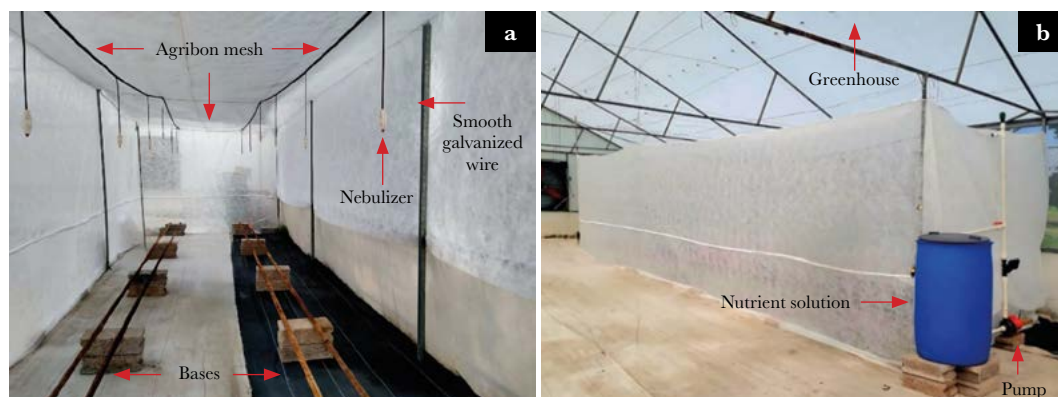


Figure 3. Cutting-rooting structure: (a) interior view and (b) exterior view.

- c) A 5-day acclimation phase was subsequently conducted under standard greenhouse conditions. Two irrigations per day were applied using full-strength (100%) nutrient solution, one at 09:00 and another at 14:00 h. In the treatment in which cuttings were rooted directly in nutrient solution, aeration was provided using an aquarium air pump (Figure 4).

Transplanting was performed 20 days after cutting rooting. Crop beds 1 m wide were used, filled with red tezontle (red volcanic rock) sand as the substrate (particle size 1-3 mm). Plants were trained to a single stem at a density of 7 plants m^{-2} of greenhouse area, and when the third inflorescence had formed, the terminal bud was removed, leaving two leaves above the third truss (Figure 5). Pollination was performed manually by shaking the wires supporting the training strings. Irrigation was applied using flexible polyethylene drip tape with integrated emitters spaced every 20 cm.

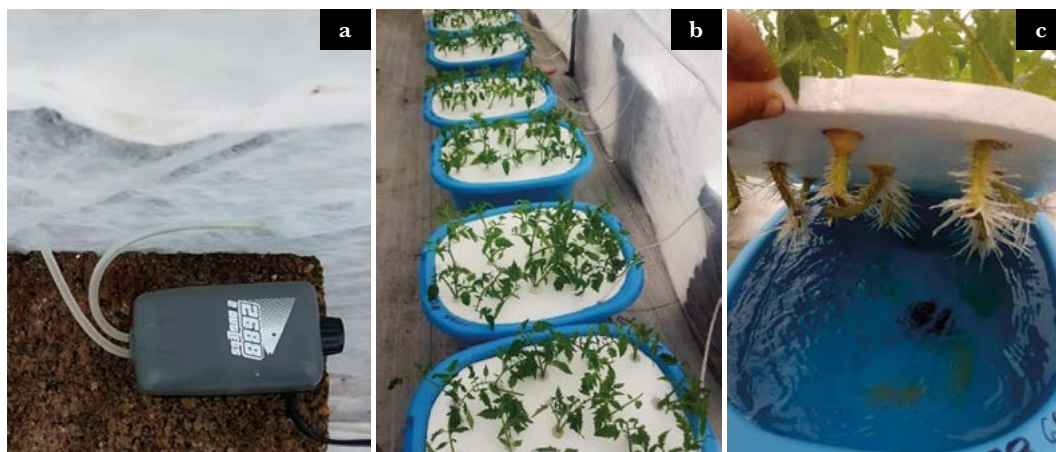


Figure 4. Aeration in Treatment 1: (a) aquarium air pump, (b) nutrient-solution treatment with oxygen supplementation, and (c) developing roots.



Figure 5. (a) Tomato plant topped at three trusses and (b) plant with two leaves above the third truss.

Data analysis

Data were first examined to verify compliance with the normality assumption. Subsequently, the variables were subjected to analysis of variance (ANOVA), and treatment means were compared using Tukey's test ($P \leq 0.05$), employing the Statistical Analysis System (SAS) for Windows, version 9.4.

RESULTS AND DISCUSSION

Variables evaluated at the seedling stage

The analysis of variance for the variables assessed at the seedling stage (data not shown) indicated a highly significant treatment effect for all measured variables, except root volume. Seedling height was greater in plants grown in peat moss than in those rooted in nutrient solution (Table 1 and Figure 6); no statistical differences were observed among the remaining treatments. Table 1 also shows that root volume did not differ among treatments. However, stem diameter, leaf area, and dry weight tended to increase in seedlings derived from cuttings rooted in nutrient solution, including statistically significant differences relative to the tezontle-only treatment. This response may be attributed to the fact that,

Table 1. Comparison of treatment means for rooting treatments in tomato seedlings (cv. Pai Pai).

Treatment	Height (cm)	Stem diameter (mm)	Leaf area (cm ²)	Root volume (cm ³)	Dry weight (g)
Nutrient solution	18.8 b	7.3 a	354.5 a	5.1 a	3.1 a
Peat moss	24.5 a	5.7 b	251.1 ab	3.1 a	2.0 ab
Fine red tezontle	19.6 ab	5.6 b	207.2 b	2.5 a	1.7 b
Tezontle + peat moss	22.6 ab	6.1 ab	269.6 ab	3.9 a	2.3 ab
LSD	5.3	1.9	129.1	2.9	1.3

Values with the same letter within each column are equal according to Tukey's test at a $P \leq 0.05$. LSD=Least significant difference.



Figure 6. Differences in seedling height as affected by treatment: (a) nutrient solution, (b) peat moss, (c) red tezontle, and (d) tezontle + peat moss mixture.

under nutrient-solution rooting, seedlings received a continuous supply of water and nutrients, as well as adequate root-zone oxygen provided by the air pump. In contrast, seedlings grown in tezontle may have experienced substrate compaction, which can impair water and nutrient uptake and reduce aeration, as reported by Vargas-Tapia *et al.* (2008), Urrestarazu-Gavilán (2004), and Urrestarazu and Carrasco (2023).

The results indicate that the use of a nutrient solution and a 1:1 (v/v) mixture of fine tezontle and peat moss are viable alternatives for rooting tomato cuttings, enabling the production of high-quality seedlings at reduced costs, as reported by Abad *et al.* (2005) and Lazcano-Bello *et al.* (2021). Although peat moss provides high moisture retention and adequate root-zone aeration, its high price reduces profitability for growers (Nava-Pérez *et al.*, 2019; Cheiri *et al.*, 2018). In addition, its use has been associated with negative environmental impacts (Muro *et al.*, 2005; Fernández-Bravo *et al.*, 2006).

Variables evaluated at the reproductive stage

Analyses of variance for reproductive-stage variables (data not shown), together with mean comparisons (Tables 2 and 3), indicated that none of the evaluated variables differed significantly among treatments.

In absolute terms, the highest yield (2.5 kg) was obtained when cuttings were rooted in the fine tezontle + peat moss mixture, corresponding to 17.5 kg m^{-2} in a production cycle lasting four months from transplanting to the end of harvest. Comparable yields have been

Table 2. Comparison of treatment means for rooting treatments in morphological variables evaluated in tomato plants at the reproductive stage.

Treatment	Height (cm)	Stem diameter (mm)	Leaf area index ($\text{m}^2 \text{m}^{-2}$)	Plant width (cm)
Nutrient solution	88.1 a	14.4 a	3.6 a	40.5 a
Peat moss	92.7 a	14.6 a	4.1 a	41.8 a
Fine red tezontle	92.3 a	13.9 a	4.4 a	42.4 a
Tezontle + peat moss	96.3 a	14.2 a	4.3 a	44.3 a
LSD	11.1	2.2	0.9	4.7

Values with the same letter within each column are equal according to Tukey's test at a $P \leq 0.05$. LSD=Least significant difference.

Table 3. Comparison of treatment means for rooting treatments in yield and its components in tomato plants.

Treatment	Number of flowers	Number of fruits	Fruit weight (g)	Yield (kg plant^{-1})
Nutrient solution	20.0 a	19.1 a	114.0 a	2.19 a
Peat moss	19.5 a	19.2 a	123.8 a	2.33 a
Fine red tezontle	20.3 a	19.2 a	112.3 a	2.16 a
Tezontle + peat moss	21.6 a	20.9 a	121.4 a	2.54 a
LSD	3.0	2.8	20.1	0.45

Values with the same letter within each column are equal according to Tukey's test at a $P \leq 0.05$. LSD=Least significant difference.

reported by Sánchez-Del Castillo *et al.* (2021) and Moreno-Pérez *et al.* (2021) for tomato plants established at high population densities using botanical seed propagation.

The results of this study suggest that the use of readily available substrates and the implementation of nutrient solution as a rooting medium for tomato cuttings constitute an economically viable option for tomato producers, while also facilitating crop management under high plant-density systems.

CONCLUSIONS

Rooting tomato cuttings in nutrient solution or in a 1:1 (v/v) mixture of peat moss and tezontle enables the production of high-quality seedlings at low cost, thereby providing a feasible alternative for managing tomato crops at high population densities.

REFERENCES

- Abad, M., Noguera, P., & Carrión, C. (2005). Sustratos para el cultivo sin suelo y fertirrigación. In: C. L. Cadahía (Ed.), *Fertirrigación, Cultivos Hortícolas y Ornamentales*. (3ra. ed., pp: 299-352.) Mundi-Prensa.
- Alconada, M., Cuellas, M., Poncetta, P., Barragán, S., Inda, E., & Mitidieri, A. (2011). Fertirrigación en cultivo de tomate protegido: Nutrición nitrogenada. Efectos en el suelo y en la producción. *Horticultura Argentina*, 30(72), 5-13. <https://www.horticulturaar.com.ar/es/pdf/85/fertirrigacion-en-cultivo-de-tomate-prottegido-i-nutricion-nitrogenada-efectos-en-el-suelo-y-en-la-produccion.pdf>
- Cheiri, K., de Gelder, A., & Peet, M. M. (2018). Greenhouse tomato production. In E. Heuvelink (Ed.), *Tomatoes* (2nd ed., pp. 276-313). CABI.
- Fernández-Bravo, C., Urdaneta, N., Silva, W., Poliszuk, H., & Marín, M. (2006). Germinación de semillas de tomate (*Lycopersicon esculentum* Mill.) cv 'Río Grande' sembradas en bandejas plásticas, utilizando distintos sustratos. *Revista De La Facultad De Agronomía De La Universidad Del Zulia*, 23(2), 188-196. <https://produccioncientificaluz.org/index.php/agronomia/article/view/26610>.
- Gaytán-Ruelas, M., Vargas-Espinoza, E., Rivera-Arredondo, M., & Morales-Félix, V. de J. (2016). Efecto del raleo de frutos en el rendimiento de jitomate (*Lycopersicon esculentum* Mill.) bajo invernadero. *Revista de Análisis Cuantitativo y Estadístico*, 3(7), 18-25. https://www.ecorfan.org/bolivia/researchjournals/Analisis_Cuantitativo_y_Estadistico/vol3num7/Revista_de_Analisis_Cuantitativo_V3_N7_3.pdf
- Lazcano-Bello, M. I., Sandoval-Castro, E., Tornero-Campante, M. A., Hernández-Hernández, B. N., Ocampo-Fletes, I., & Díaz-Ruíz, R. (2021). Evaluación de sustratos, solución nutritiva y enraizador en producción de plántulas de jitomate. *Revista mexicana de ciencias agrícolas*, 12(1), 61-76. <https://doi.org/10.29312/remexca.v12i1.2450>
- Mejía-Betancourt, F. A., Sánchez-Del Castillo, F., Moreno-Pérez, E. C., & González-Molina, L. (2023). Esquejes enraizados, una alternativa para la producción de jitomate bajo invernadero en ciclos cortos. *Revista Mexicana de Ciencias Agrícolas*, 14(3), 389-399. <https://doi.org/10.29312/remexca.v14i3.3038>
- Moreno-Pérez, E. C., Sánchez-Del Castillo, F., Ruiz-Díaz, M., & Contreras-Magaña, E. (2021). Effect of population densities and paclobutrazol applications on seedling quality and yield in tomato. *Revista Chapingo Serie Horticultura*, 27(1), 5-17. <https://doi.org/10.5154/r.rchsh.2020.05.010>
- Moreno-Pérez, E. del C., Sánchez-Del Castillo, F., González-Molina, L., Contreras Magaña, E., & Messina, F. R. (2016). Métodos de enraizamiento de esquejes para la producción de jitomate (*Solanum lycopersicum* L.) hidropónico. *Revista Agroproductividad*, 9(10), 50-55. <https://revista-agroproductividad.org/index.php/agroproductividad/article/view/831>
- Muro, J., Irigoyen, I., Samitier, P., Mazuela, P., Salas, M., Soler, J., & Urrestarazu, M. (2005). Wood fiber as growing medium in hidroponic crops. *Acta Horticulturae*, 697, 179-185. <https://doi.org/10.17660/ActaHortic.2005.697.22>
- Nava-Pérez, E., Valenzuela-Quiñónez, W., & Rodríguez-Quiroz, G. (2019). El vermicompost como sustrato sustituto en la germinación de tomate (*Solanum lycopersicum* L.). *Agrociencia*, 53(6), 869-880. <https://ipn.elsevierpure.com/es/publications/el-vermicompost-como-sustrato-sustituto-en-la-germinaci%C3%B3n-de-toma>
- Ortega-Martínez, L. D., Sánchez-Olarte, J., Ocampo-Mendoza, J., Sandoval-Castro, E., Salcido-Ramos, B. A., & Manzo-Ramos, F. (2010). Efecto de diferentes sustratos en crecimiento y rendimiento de tomate

- (*Lycopersicon esculentum* Mill) bajo condiciones de invernadero. *Ra Ximhai*, 6(3), 339-346. <https://doi.org/110.35197/rx.06.03.2010.02.lo>
- Sánchez-Del Castillo, F., Moreno-Pérez, E. del C., & Contreras-Magaña, E. (2012). Development of alternative commercial soilless production systems I: Tomato. (Proceedings of the Second International Symposium on Soilless Culture and Hydroponics). *Acta Horticulturae*, 947, 179-187. <https://doi.org/10.17660/ActaHortic.2012.947.22>
- Sánchez-Del Castillo, F., Portillo-Márquez, L., Moreno-Pérez, E. C., Magdaleno-Villar, J. J., & Vázquez-Rodríguez, J. C. (2021). Efectos del volumen de contenedor y densidad de plántula sobre trasplante tardío y número de flores en jitomate. *Revista Chapingo Serie Horticultura*, 27(2), 71-84. <https://doi.org/10.5154/r.rchsh.2020.06.015>
- Sánchez-Del Castillo, F., Moreno-Pérez, E. C., Coatzín, R. R., Colinas León, M. T., & Peña López, A. (2010). Evaluación agronómica y fisiotécnica de cuatro sistemas de producción en dos híbridos de jitomate. *Revista Chapingo Serie Horticultura*, 16(3), 207-214. <https://revistas.chapingo.mx/horticultura/revista/articulos/viewer.html?file=rchshXVI808.pdf>
- Servicio de Información Agroalimentaria y Pesquera. (2023). Panorama Agroalimentario 2023, la edición estadística más importante del sector agroalimentario. <https://www.gob.mx/siap/acciones-y-programas/panorama-agroalimentario-258035>
- Urrestarazu-Gavilán, M., & Carrasco-Silva, G. (2023). *Soilless Culture and Hydroponics*. Edit Mundi-prensa. (1ra. Edición). Madrid, ES. 279 P.
- Urrestarazu-Gavilán, M. (2004). *Tratado de cultivo sin suelo*. Edit Mundi-prensa. (3ra. Edición). Madrid, ES. 914 p.
- United States Department of Agriculture (2024). *Tomatoes and products annual: Mexico 2024 report*. <https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName>
- Vargas-Tapia, P., Castellanos-Ramos, J. Z., Muñoz-Ramos, J. J., Sánchez-García, P., Tijerina-Chávez, L. López-Romero, R. M., Martínez-Sánchez, C., & Ojodeagua-Arredondo, J. L. (2008). Efecto del tamaño de partícula sobre algunas propiedades físicas del tezontle de Guanajuato, México. *Agricultura técnica en México*, 34(3), 323-331. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0568-25172008000300007&lng=es&tlng=es.

Introduction and use of Citlali and Ameyali potato varieties in family gardens in Zinacantepec, Mexico

Marín-Casimiro, Maricela¹; Flores-López, Román^{1*}; Flores-Gutiérrez, Francisco X.²; Soria-Ruiz, Jesús¹; Sotelo-Ruiz, Erasto¹

¹ Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Sitio Experimental Metepec. Km. 4.5, Carretera Toluca-Zitácuaro, Vialidad Adolfo López Mateos, Col. San José Barbabosa, Zinacantepec, Estado de México. C.P. 51350.

² Universidad Autónoma del Estado de México. Facultad de Ciencias Agrícolas. Campus Universitario “El Cerrillo”, El Cerrillo Piedras Blancas, Toluca, Estado de México. C. P. 50200.

* Correspondence: flores.roman@inifap.gob.mx; rammarin1989@gmail.com

ABSTRACT

Objective: To introduce and evaluate the performance of the Citlali and Ameyali potato varieties in agroecologically managed home gardens within a rural community, compared to the Dutch variety Fianna.

Design/Methodology/Approach: A randomized block design was implemented, using home gardens as experimental units. Three agricultural cycles were conducted: Cycle one (March-July 2022), cycle two (October-December 2022), and cycle three (June-September 2023).

Results: No significant differences were found in fresh tuber weight per plant among the varieties tested. In the first cycle, yields from Ameyali and Citlali did not differ significantly. However, in cycles two and three, statistically significant differences were observed. Yields decreased in Citlali and Fianna during these cycles due to damage caused by late blight, which affected both foliage and tubers. In contrast, Ameyali demonstrated greater tolerance to late blight.

Findings/Conclusions: Potato production in agroecologically managed home gardens is feasible for small-scale producers in San Antonio Acahualco, Zinacantepec, particularly when using varieties tolerant to late blight (*Phytophthora infestans*) and *Bactericera cockerelli*.

Keywords: variety, home gardens, agroecology, late blight, potato

Citation: Marín-Casimiro, M., Flores-López, R., Flores-Gutiérrez, F. X., Soria-Ruiz, J., & Sotelo-Ruiz, E. (2026). Introduction and use of Citlali and Ameyali potato varieties in family gardens in Zinacantepec, Mexico. *Agro Productividad*. <https://doi.org/10.32854/1h62nv29>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

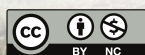
Received: June 14, 2024.

Accepted: January 27, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 107-114.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Home gardens are agricultural ecosystems located near households, where ecological, agronomic, cultural, and social processes converge (Santana *et al.*, 2015; Rivas, 2014). These systems enable crop production tailored to the living conditions and needs of each family (Chablé *et al.*, 2015), while also providing opportunities to generate additional income through the sale of surplus vegetables (Nicholls *et al.*, 2019). Furthermore, they serve as refuges for wild plant species that have disappeared from their natural habitats (White *et al.*, 2014). The potato (*Solanum tuberosum* L.) is native to the Andes and has been



cultivated for over 7,000 years (Román *et al.*, 2015). It is one of the world's most important food crops, following rice, maize, and wheat (Zhang *et al.*, 2017). Potato cultivation is vulnerable to both biotic and abiotic factors that can reduce yields and compromise product quality (Dahal *et al.*, 2019; Mohanta *et al.*, 2017). The most significant disease affecting potato crops globally is late blight, caused by the oomycete *Phytophthora infestans*, which can devastate entire fields within days if not properly managed, resulting in substantial economic losses (Fry *et al.*, 2015; Lenman *et al.*, 2016). Commercial potato varieties typically have a vegetative cycle ranging from 90 to 160 days. In Mexico, the most commonly cultivated varieties for fresh consumption include Fianna, Orquesta, Caesar, and Ambra, among others. The National Institute of Forestry, Agricultural and Livestock Research (INIFAP) has released several varieties with resistance and/or tolerance to late blight (*Phytophthora infestans*) and potato psyllid (*Bactericera cockerelli*), with industrial-grade quality and smooth skins suitable for washing. These varieties contain 19-21% dry matter and include Citlali and Ameyali, which offer yields between 50 and 70 tons per hectare. They are adaptable to altitudes ranging from 50 to 3,400 meters above sea level and are suitable for cultivation across all recommended potato-producing regions of the country, during both spring-summer and autumn-winter cycles (González *et al.*, 2021).

MATERIALS AND METHODS

The present study was conducted in the community of San Antonio Acahualco, municipality of Zinacantepec, Mexico (19° 17' 00" N latitude and 99° 44' 00" W longitude). The prevailing climate is temperate sub-humid. The area is dominated by Andosol, Cambisol, Phaeozem, and Regosol soils. Land use in the region is primarily for seasonal rainfed agriculture. The main crops are grain and forage maize, potatoes, fava beans, and peas (SEDUI, 2024).

Experimental design

A randomized block design was implemented, with each block corresponding to a home garden (60 m² area, 5 m wide × 12 m long). The blocks belonged to female producers from the community of San Antonio Acahualco. The research employed both qualitative and quantitative methods, under technical guidance, and was carried out through exploratory and descriptive analysis. Three agricultural cycles of potato cultivation were conducted: cycle one from March to July 2022; cycle two from October to December 2022; and cycle three from June to September 2023. In each cycle and block, random sampling was performed by selecting five plants per variety, considering the following variables: a) physicochemical analysis of the manure used in each block (in cycle two); b) fresh tuber weight; c) number of tubers per plant; and d) quantification of damage caused by climate, diseases, and pests. An analysis of variance and mean comparison among blocks and varieties was conducted using the Tukey test ($p \leq 0.05$), at a 5% significance level, with the InfoStat software, version 2008 (Di Rienzo *et al.*, 2010). For the qualitative variables, only a description of climate damage, disease symptoms, pest infestation on plants, and tuber damage was performed.

The activities carried out included 1) land leveling; 2) design and preparation of planting beds; 3) disinfection and planting of seed tubers; 4) soil fertilization using the manure available to each producer; 5) foliar fertilization with biofertilizers; 6) pest and disease control using plant extracts and mineral broths; 7) irrigation; 8) sampling and 9) harvesting. The experiment was conducted under an agroecological management approach, considering the interaction of potato crops with other vegetables (leafy, root, bulb, flower, and fruit types) and some medicinal plants.

The genetic material used as seed was provided by INIFAP, consisting of the Citlali and Ameyali potato varieties, as well as the Fianna variety used as a control, which is the most widely cultivated in Mexico. Table 1 shows the amount of manure used in each block, which was applied in two stages: the first at planting, and the second 20 days after the emergence of the seed tuber. Crop nutrition was complemented with foliar applications of biofertilizers three times per week (manure tea at 20 mL L^{-1} ; supermagro at 20 mL L^{-1} during the vegetative stage; and banana peel tea at 20 mL L^{-1} during the tuber filling stage).

Agroecological management in this study aimed to minimize the impact on the territory and on the animal and plant species present in the home gardens, while promoting more efficient use of natural resources. The incorporation of various organic sources contributed to increased yield and preservation of ancestral agricultural practices, while also improving the physical, chemical, and biological properties of the soil (Alaluna & Villagarcía, 2000; Bolo *et al.*, 2020).

RESULTS AND DISCUSSION

Physicochemical analysis of the manure

In the second cycle, a one-kilogram sample of the manure used for plant fertilization was collected from each block. All samples were sent to the Soil Science Laboratory of the Faculty of Agricultural Sciences at UAEMEX, Toluca, State of Mexico, where physicochemical analyses were performed. Table 2 shows the differences in the nutritional content of the manures applied across the blocks.

Nitrate content in Blocks I and III was three times higher than in Blocks II and IV. Nitrate availability helps maintain a functional leaf area for a longer period, directly enhancing photosynthetic activity and promoting the translocation of photoassimilates to

Table 1.

Block	Type of manure	Total amount of manure m^{-2}		
		Cycle 1	Cycle 2	Cycle 3
I	Bovine manure 100 %	7.0 kg m^{-2}	14 kg m^{-2}	6.6 kg m^{-2}
II	Manure: sheep 60 %, poultry 30 % and rabbit 10 %.	5.2 kg m^{-2}	10.8 kg m^{-2}	--
III	Manure: bovine 30 %, sheep 30 % and equine 40 %.	10.5 kg m^{-2}	10.7 kg m^{-2}	9.0 kg m^{-2}
IV	Mmanure: rabbit 20 %, sheep 70 % and poultry 10 %.	4 kg m linear	6.25 g m^{-2}	6.5 kg m^{-2}

Table 2.

Physicochemical Parameter	Block I	Block II	Block III	Block IV
Organic Matter (%)	24.96	30.42	23.40	23.40
pH	9.85	10.50	8.50	8.70
Electrical Conductivity (dS/m)	0.27	0.73	0.22	0.30
Apparent Density (g/cm ³)	1.12	1.75	1.30	1.60
Nitrates (ppm)	5.488	1.392	6.192	2.336
Phosphorus (ppm)	576.03	922.74	851.76	958.23
Potassium (ppm)	7,878	2,067	4,173	7,956
Calcium (ppm)	3,064	3,098	3,098	3,098
Magnesium (ppm)	292.50	163.80	287.04	366.60
Aluminum (ppm)	156,000	23,400	43,920	135,720

Note: pH=potential of hydrogen; E.C.=electrical conductivity; A.D.=apparent density; Mg=magnesium; P=phosphorus; K=potassium; Ca=calcium; Al=aluminum; ppm=parts per million.

storage organs (Ghemam *et al.*, 2016). In contrast, Block I had the lowest phosphorus content, with 576.03 ppm equivalent to only 60% of the value found in Block IV, which had the highest concentration and was considered as 100%. Regarding potassium, Blocks I and IV showed higher concentrations, exceeding 7,000 ppm, while Blocks II and III recorded significantly lower levels, representing only 25.9% and 52.5% of the highest value, respectively.

Fresh tuber weight per plant

In the first cycle, no statistically significant differences were found between the means of the Ameyali and Citlali varieties. However, Citlali had the highest average fresh tuber weight, with 493.25 g per plant, compared to Ameyali (Figure 1). In the second cycle, where Ameyali and the control variety Fianna were evaluated, a significant difference was observed between their means. Fianna had a higher average weight (301.7 g per plant),

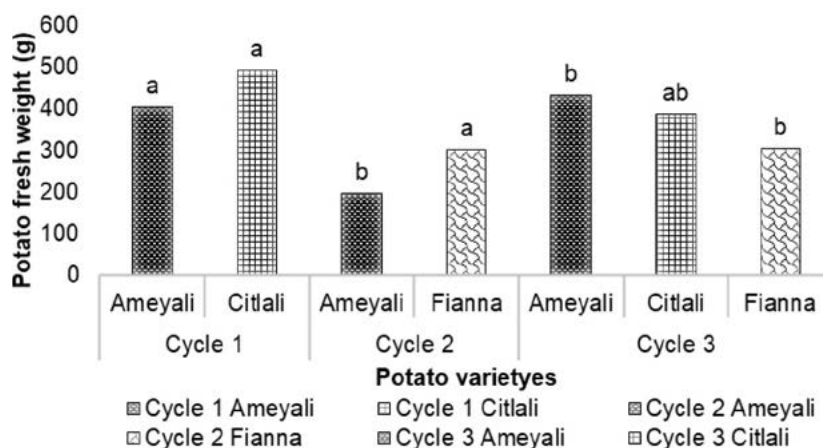


Figure 1. Mean comparison of fresh tuber weight for the Ameyali, Citlali, and Dutch variety Fianna in home gardens of San Antonio Acahualco, Zinacantepec. Means followed by the same letter are not statistically different (Tukey, $p \leq 0.05$).

which was attributed to frost damage affecting more than 80% of Ameyali plants. In the third cycle, no statistically significant differences were found among varieties; however, Ameyali showed a higher average weight (432.44 g per plant) than Citlali and Fianna. During this cycle, all three varieties were affected by late blight, which caused damage to both plants and tubers, with Ameyali demonstrating greater tolerance to the disease.

Total number of tubers per plant

As shown in Figure 2, in the first cycle there was no statistically significant difference between the means of the Ameyali and Citlali varieties. However, Citlali stood out with an average of 12 tubers per plant. In the second cycle, a significant difference was observed between Ameyali and Fianna, with averages of 8 and 10 tubers per plant, respectively. In the third cycle, statistically significant differences were observed among Ameyali, Citlali, and Fianna. Although Citlali and Fianna produced a higher number of tubers, these were of lower weight. The smaller tuber size was attributed to damage caused by late blight, which affected plant health and led to premature death, preventing the completion of the vegetative cycle..

Quantification of damage caused by climate, diseases, and pests

During all three cultivation cycles, a diagnosis was conducted as part of the technical assistance, evaluating damage caused by frost and rainfall, plant and tuber diseases, and pest infestations. Damage was classified into three categories: severe, minor, and absent. In the first cycle, pest problems were observed, including whiteflies, aphids, and cutworms, as well as damage caused by *Spongospora subterranea*. The latter was classified as severe, as it affected a large portion of the tubers in both the Citlali and Ameyali varieties (Table 3).

In the second cycle, whiteflies, aphids, leafhoppers, and cutworms were recorded. Block I experienced damage from late blight, frost, and pocket gophers, affecting 17 Ameyali plants. In Block III, Ameyali was also affected by frost. In the third cycle, all blocks were affected by late blight. The Fianna variety (control) showed 100% damage, while Ameyali showed 16% of damaged plants, and Citlali showed 20%. During cycles two and three,

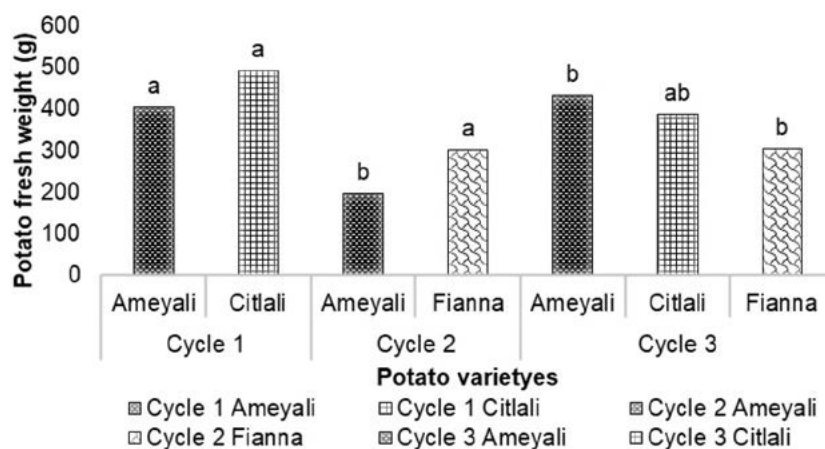


Figure 2. Total number of tubers per plant across three vegetative cycles in backyard gardens (blocks).

Table 3.

Vegatative cycle	Variety	Block	Pests			Diseases		Environmental factors
			1	2	3	4	5	
Cycle 1	Ameyali	I	++	-	-	++	-	-
		II	++	++	-	++	-	-
		III	++	++	-	++	-	-
		IV	-	++	-	++	++	++
	Citlali	I	-	++	-	++	-	-
		II	++	+	-	++	-	-
		III	++	-	-	++	-	-
		IV	-	++	-	++	-	++
Cycle 2	Ameyali	I	++	++	-	+	++	+
		II	++	-	-	+	-	++
		III	+	-	+	+	+	-
		IV	-	-	-	+	-	-
	Fianna	I	++	++	-	+	+	-
		II	+	-	-	-	++	+
		III	+	-	+	+	-	-
		IV	+	-	-	+	-	-
Cycle 3	Ameyali	I	++	++	+	+	+	+
		II	-	-	-	-	-	-
		III	-	-	+	+	+	+
		IV	++	++	++	+	++	++
	Citlali	I	++	++	+	+	++	++
		II	-	-	-	-	-	-
		III	-	-	+	+	+	-
		IV	++	++	++	++	++	++
	Fianna	I	++	++	+	+	++	++
		II	-	-	-	-	-	-
		III	-	-	+	+	++	++
		IV	++	++	++	+	++	++

++=Major damage; +=Average damage; -=No damage. Pests: 1=Aphip; 2=White fly and 3=Choppers. Diseases: 4=Subterranean Spongospora and 5=late blight.

weekly applications of silico-sulfo-calcium broth (an insecticide-fungicide-nutrient solution) were made to the soil to control *Spongospora subterranea*. As a result, disease incidence was reduced, with symptoms appearing only as small spots, and typically affecting no more than one or two tubers per plant.

In the second and third cycles, the presence of late blight was observed in the Citlali and Fianna varieties, affecting both plants and tubers, which resulted in decreased yields. In contrast, the Ameyali variety demonstrated resistance to the disease, with only partial damage to the plant. According to Niks *et al.* (2019), Gabriel *et al.* (2016), Moncayo *et al.*

(2019), and Rubio *et al.* (2016), effective pest and disease prevention and control throughout the crop cycle reduces yield losses. In addition, genetic resistance is considered an active plant defense mechanism in crop management.

CONCLUSIONS

The women producers involved in this study recognized that the Ameyali variety developed by INIFAP delivered better yields compared to the Citlali variety. Both varieties were noted for their tuber quality, particularly in terms of taste, color, and suitability for food processing. Ameyali exhibited resistance to late blight and potato purple top wilt, despite the challenges posed by seasonal changes. However, the control variety Fianna was significantly affected by late blight, which compromised its yields.

ACKNOWLEDGMENTS

We thank the participating women producers for their collaboration in introducing the Citlali and Ameyali potato varieties in home gardens in San Antonio Acahualco, Zinacantepec, Mexico.

REFERENCES

- Alaluna, E. y Villagarcía, S. 2000. Evaluación del efecto de fertilización, aplicación de estiércol y absorción de elementos en el rendimiento de la secuencia papa-kiwicha, evaluado mediante la técnica del elemento faltante. *Rev. Peruana de Biología*. 7(2):115-123.
- Bolo, J. D.; Reynoso, A.; Cosme, R. C.; Arone, G. y Calderón, C. 2020. La aplicación combinada de abonos orgánicos mejora las propiedades físicas del suelo asociado al cultivo de quinua (*Chenopodium quinoa* Willd.). *Sci. Agropec.* 17(3):401-408. <http://www.scielo.org/pe/scielo.php?pid=S2077-99172020000300401&script=sci-arttext>.
- Chablé, R., Palma, D., Vázquez, C., Ruiz, O., Mariaca, R. y Ascencio, J. 2015. Estructura, diversidad y uso de las especies en huertos familiares de la Chontalpa, Tabasco, México. *Ecosistemas y Recursos Agropecuarios* 2(4): 23-39. <https://www.scielo.org.mx/pdf/era/v2n4/v2n4a3.pdf>
- Di Rienzo J. A.; Casanoves, F. Balzarini, M. G.; Gonzalez. L.; Tablada, M. y Robledo, C. W. 2010. InfoStat. Grupo InfoStat; Universidad Nacional de Córdoba, Argentina. Available. <http://www.infostat.com.ar>
- Fry, W. E., Birch, P. R. J., Judelson, H. S., Grünwald, N. J., Danies, G., Everts, K.L., Gevents, A. J., Gugino, B. K., Johnson, D. A., Johnson, S. B., McGrath, M. T., Myers, K. L., Ristaino, J. B., Roberts, P. D., Secor, G., & Smart, C. D. (2015). Five reasons to consider *Phytophthora infestans* a reemerging pathogen. *Phytopathology*, 105(7), 966-981. <https://doi.org/10.1094/PHYTO-01-15-0005-FI>
- Ghemam, D.; Zeid, A.; Khaled, K.; Chems, A.; Bachir, K. and Mohammed, S. 2016. Effects the application of some organic manures with nitrogen levels on the growth and productivity of potato in the Algeria South. *Inter. J. Agric. Environ. Res.* 2(4):982-991. <https://www.researchgate.net/publication/308605569-Effectsthe-application-of-someorganic-manures-with-nitrogenlevels-onthe-growth-and-productivity-of-potatointheAlgeria-south>.
- González, E.; Ramírez, M.; Canul-Ku, J.; Flores, R. y Macías, L. (2021). Aportaciones del Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias al mejoramiento genético de hortalizas. *Revista Mexicana de Ciencias Agrícolas*. 1-13. [10.29312/remexca.v1i2i25.2802](https://doi.org/10.29312/remexca.v1i2i25.2802).
- Lenman, M., Ali, A., Mühlenbock, P., Carlson-Nilsson, U., Liljeroth, E., Champouret, N., Vleeshouwers, V. G. A., Andreasson, E. (2016). Effector-driven marker development and cloning of resistance genes against *Phytophthora infestans* in potato breeding clone SW93-1015. *Theoretical and Applied Genetics*, 129, 105-115. <https://doi.org/10.1007/s00122-015-2613-y>
- Mohanta, T. K., Bashir, T., Hashem, A., & Abd-Allah, E. F. (2017). Systems biology approach in plant abiotic stresses. *Plant Physiology and Biochemistry*, 121, 58-73. <https://doi.org/10.1016/j.plaphy.2017.10.019>
- Moncayo, J., Delgado, R., Marcillo, C., Salazar, C., & Nicks, R. E., Parlevliet, J. E., Lindhout, P., & Bai, Y. (2019). Breeding crops with resistance to diseases and pests. Wageningen Academic Publishers. <https://doi.org/10.3920/978-90-8686-882-7>
- Rivas, G. (2014). Huertos familiares para la conservación de la agrobiodiversidad, la promoción de la seguridad alimentaria y la adaptación al cambio climático. *Ambientico* 243: 4-9. <https://www.redalyc.org/pdf/3605/360549889007.pdf>

- Rubio, O., Cadena, M., & Flores, R. (2016). Comparación de la resistencia horizontal y vertical contra el tizón tardío de la papa en Toluca. *Revista Mexicana de Ciencias Agrícolas*, 7(4), 755-766. <https://www.redalyc.org/pdf/2631/263146721003.pdf>
- Santana, M. R., Navarrete, D. y Mateo, J. J. (2015). Riqueza de especies en huertos caseros de tres municipios de la región Otomí Tepehua, Hidalgo, México. In: F. Montagnini, E. Somarriba, E. Murgueitio, H. Fassola y B. Eibl . Sistemas agroforestales. Funciones productiva, socioeconómica y ambiental. CATIE, Costa Rica, pp. 405-422. https://rmae.voaxaca.tecnm.mx/wp-content/uploads/2020/11/8-RMAE_2016-04-Huertos-To-edit.pdf
- Secretaria de Desarrollo Urbano e Infraestructura (SEDUI) (2024). Plan municipal de desarrollo urbano zinacantepec. Disponible. https://sedui.edomex.gob.mx/sites/sedui.edomex.gob.mx/files/files/planes_municipales/Zinacantepec/PMDU_ZINACANTEPEC.pdf
- White, L., J. Juan, C. Chávez, y J. Gutiérrez. (2013). Flora medicinal en San Nicolás, municipio de Malinalco, Estado de México. *Polibotanica* 35: 173-206. <https://www.redalyc.org/pdf/621/62125675010.pdf>
- Zhang, S., Zheng, X., Reiter, R. J., Feng, S., Wang, Y., Liu, S., Jin, L., Li, Z., Datla, R., Ren, M. (2017). Melatonin attenuates potato late blight by disrupting cell growth, stress tolerance, fungicide susceptibility and homeostasis of gene expression in *Phytophthora infestans*. *Frontiers in Plant Science*, 8, 1993. <https://doi.org/10.3389/fpls.2017.01993>



Dragon fruit (*Hylocereus undatus*) crop yield: an analysis of innovations

López-Chávez, Anahí¹; Alvarado-Raya, Horacio E.^{1*}; Estrada-Chavira, María E.²; Altamirano-Cárdenas, J. R.¹

¹ Universidad Autónoma Chapingo, carretera federal México-Texcoco km 38.5, Texcoco, Estado de México, México. C. P. 56230.

² Tecnológico Nacional de México/Tecnológico de Estudios Superiores de Ixtapaluca. Carretera Coatepec, Callejón San Juan 7. Ixtapaluca, Estado de México, México. C.P. 56580.

* Correspondence: halvarador@chapingo.mx

ABSTRACT

Objective: to analyze the impact of innovations on the productivity of pitahaya cultivation in the state of Puebla, Mexico.

Design/Methodology/Approach: twenty-six pitahaya producers were surveyed in seven municipalities of Puebla. The profiles of producers were analyzed in terms of education and age. Thirty activities that influence crop productivity were evaluated, and the innovation adoption indices (InAI) and innovation adoption rates (IAR) were calculated.

Results: the average IAR (innovation adoption rate) is below 40%. The application of organic matter as a soil amendment is the most widely adopted practice, while management and financial record-keeping are areas that producers have neglected. Crucial activities for improving productivity that producers should implement were identified, such as post-harvest fruit handling, pollination management, and genetic management. Our results suggest that these activities may be poorly executed.

Limitations/Implications of the study: the low availability of time of the producers and the large size of the area, generate difficulties for face surveys or more extent and frequent field visits.

Findings/Conclusions: a trend was found, although not universal, indicating that higher InAI is associated with higher crop yield. Therefore, the correct implementation of innovative activities is crucial for improving yield.

Keywords: innovation adoption index, innovation adoption rate, indexes, productivity, pitahaya, nutraceutical fruits.

Citation: López-Chávez, A., Alvarado-Raya, H. E., Estrada-Chavira, M. E., & Altamirano-Cárdenas, J. R. (2026). Dragon fruit (*Hylocereus undatus*) crop yield: an analysis of innovations. *Agro Productividad*. <https://doi.org/10.32854/k2vm3q74>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: August 5, 2025.

Accepted: January 22, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 115-121.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Dragon fruit (*Hylocereus undatus*), called pitahaya in Mexico, is an exotic fruit with sweet pulp that has gained popularity in international markets in recent decades, due to its flavor and nutraceutical contributions (Ramírez, 2007).



In Mexico, pitahaya cultivation has experienced a notable increase in production, as observed in the state of Puebla (ASERCA, 2000). This phenomenon is largely due to innovations in cultivation techniques and agricultural management, which have significantly contributed to improving the quality and quantity of the fruit in this region (Ortiz-Hernández, 2000; Nerd *et al.*, 2002; Santacruz-Vázquez *et al.*, 2009).

Puebla, a state located in central Mexico, offers ideal climatic and geographic conditions for dragon fruit cultivation (Valiente-Banuet *et al.*, 2007). Warm temperatures and moderate altitude provide a favorable environment for the development of this species, which has fostered steady growth in dragon fruit production in the region (SIACON, 2023). Furthermore, cultivation techniques and agricultural practices have evolved significantly over the years (Meraz-Alvarado *et al.*, 2003).

This study aimed to investigate and analyze in depth the influence of various innovations in agricultural management on the productivity of dragon fruit cultivation in Puebla. Advances in cultivation techniques, pest and disease management, irrigation systems, fertilization, and harvesting practices, among other relevant aspects, were examined. Through this analysis we intend not only to document the progress made in dragon fruit cultivation in the region, but also to understand the role these innovations have played in this crop expansion and consolidation as a strategic agricultural activity.

Furthermore, we seek to highlight the relevance of dragon fruit as a crop with high potential to contribute to the sustainable development of agriculture in Puebla and to generate new economic opportunities in other parts of the country. For all the above, the objective was to analyze the impact of innovations on the productivity of dragon fruit cultivation in the state of Puebla, Mexico.

MATERIALS AND METHODS

An environmental analysis was conducted to identify the largest and most productive areas for this crop in the state of Puebla. The information sources consulted for this analysis belong to institutions, universities, and research centers such as USDA (2022), SIACON (2023), and INIFAP (2023).

The methodology was based on the recommendations made by Brandenburger and Nalebuff adapted by Muñoz & Santoyo (2011), starting with the design of a baseline survey that included categories of personal data and some details of the activity, such as the influence it has on their income and the time they have managed this crop; questions related to the dynamics of sales and the different technologies they implement in the cultivation systems were included.

Twenty-six dragon fruit producers from seven municipalities in the state of Puebla were interviewed. The 'snowball' sampling method proposed by Goodman (1961) was used. The baseline survey focused on 36 basic activities for optimal crop development, classified into seven categories: nutrition, health, reproduction, establishing and management of plantations, types of trellising systems, administration, harvesting, and post-harvest handling.

Once the information was systematized, the values of the innovation adoption index (InAI) and the innovation adoption rate (IAR) were determined using the methodology of Muñoz *et al.* (2007) with the following equations:

$$InAI_{jk} = \frac{\sum_{i=1}^n Innov_{jk}}{n}$$

where: $InAI_{ik}$ is the innovation adoption index of the i -th producer in the k -th category; $Innov_{jk}$ is the presence of one innovation of the k -th category in the management of a j -th producer; n is the total number of innovations in the k -th category.

$$IAR = \frac{\text{Number of producers adopting the X innovation}}{\text{Total number of innovations}} \times 100$$

where: IAR is the innovation adoption rate, which is equal to the number of producers adopting the X innovation divided by the total of interviewed producers that adopt innovation, then this quotient is multiplied by 100 to get the value in percentage. These values were proposed to determine the innovative capacity of producers by quantifying the number of practices implemented by one producer at a given time, in regard to the total number of practices that must be done to achieve efficiency.

Graphs were prepared to allow comparisons and analysis of trends and behaviors presented by the parameters of the research, based on the information collected in the surveys.

RESULTS AND DISCUSSION

The implementation of 30 activities was evaluated, which influenced crop productivity of dragon fruit. The information obtained shows that the surveyed producers have varied profiles. The highest level of education is doctorate, but junior-high education accounts for the majority of respondents (26). The average age of producers is 42 years. Regarding the innovation adoption index, InAI values ranged from 0.15 to 0.7, with an average of 0.37 for this index (Figure 1).

In the innovation adoption rate (Figure 2), the overall IAR average was below 40%. The practice with the highest adoption rate is the incorporation of organic matter into the

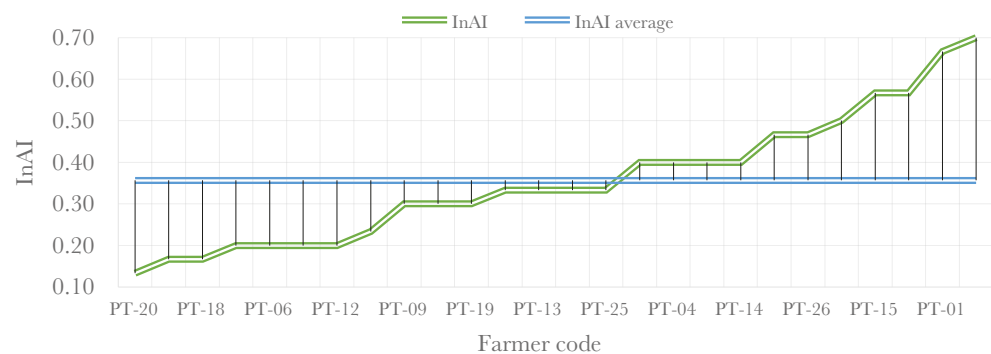


Figure 1. Innovation adoption index (InAI) for each of the producers interviewed in the state of Puebla, Mexico. Eje X: Producer; Eje Y: InAI; Legend: InAI, InAI average

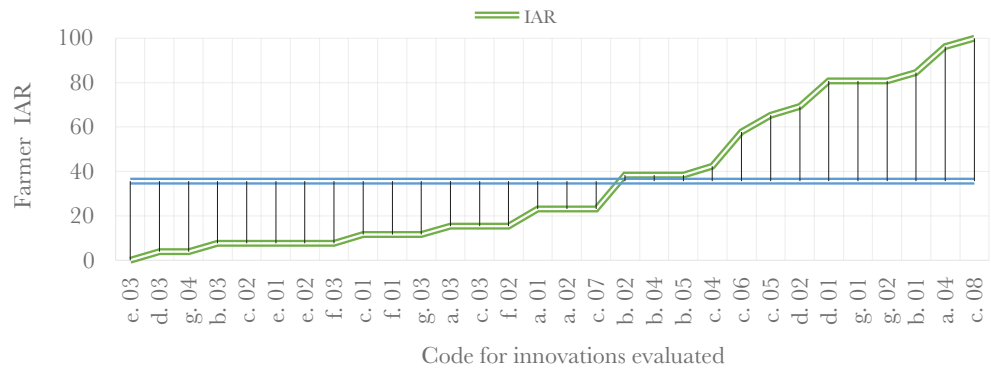


Figure 2. Innovation adoption rates (IAR) of 26 producers of dragon fruit (*Hylocereus undatus*) in the state of Puebla, Mexico. Eje X: Innovations evaluated; Eje Y: IAR of the producers.

soil, while key activities such as agricultural management, financial and administration record-keeping are completely neglected by all the producers (100%).

The analysis made it possible to identify fundamental practices to address persistent problems in the production system, including the proper handling of ripe fruit on the plant to avoid damage by birds, an efficient pollination system, and germplasm management. All of which are aimed at improving productivity and strengthening an integrated pest and disease control.

Regarding these three critical areas, although all producers claim to be taking steps to address them, the results we obtained are varied. This suggests that, while there is a general awareness of the importance of these aspects, many producers may lack the necessary technical information to implement them correctly; this leads to variability in the levels of productivity achieved.

For the group of producers interviewed, results show an overall trend in which a higher innovation adoption index (InAI) is associated with increased crop yield. However, cases were also identified where this relationship was not consistently observed (Figure 3). This situation suggests that, although producers may implement innovative practices, these may not be executed properly, limiting their effectiveness and preventing them from generating a positive impact on dragon fruit yield.

Based on the InAI values related to the different innovation categories, reclassified by municipality (Figure 4 and Figure 5), we observed that even though 96% of producers reported taking action on crop nutrition, those with the best yield results focused their innovations on nutrition (Figure 4). These improvements were achieved throughout management, through technical assistance, soil analysis, and organic and chemical-based nutrition. Whereas, producers with low yields mentioned that they added organic matter only at the time of planting.

Lira (2011) evaluated the effect of different organic fertilizers and nutrient solutions on dragon fruit plant growth, obtaining significant effects on its vegetative development. According to the graph curves, in these municipalities it is also necessary to address plant health (Figure 5), focusing on integrated pest and disease management. It is key, as well,

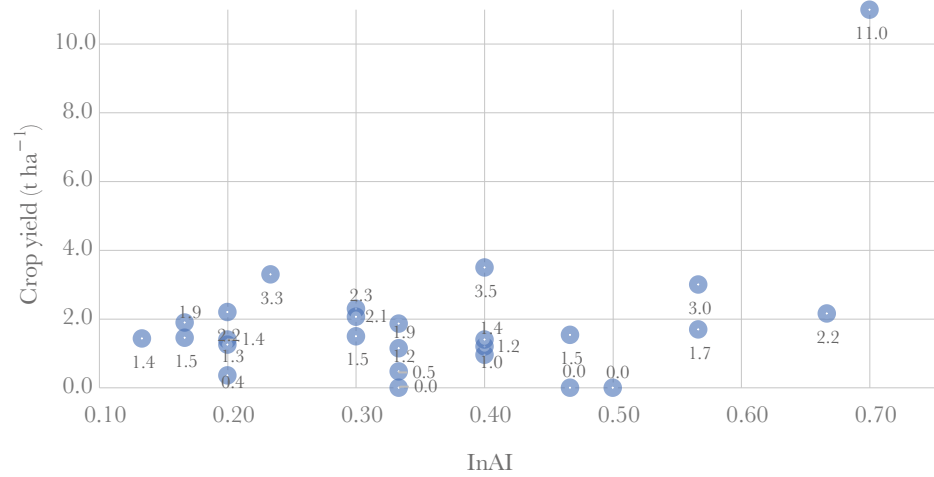


Figure 3. Relation of the innovation adoption index (InAI) to crop yield of dragon fruit (*Hylocereus undatus*) for producers in the state of Puebla, Mexico. Eje Y: Crop yield (t ha⁻¹); Eje X: InAI.

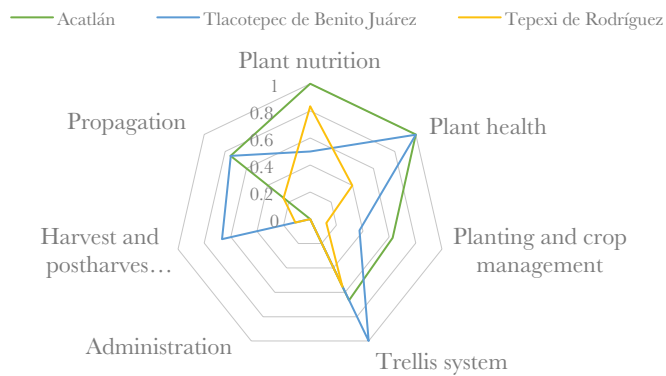


Figure 4. Innovation Adoption Index (InAI) by innovation category of the most outstanding municipalities in dragon fruit (*Hylocereus undatus*) yield in the state of Puebla, Mexico.

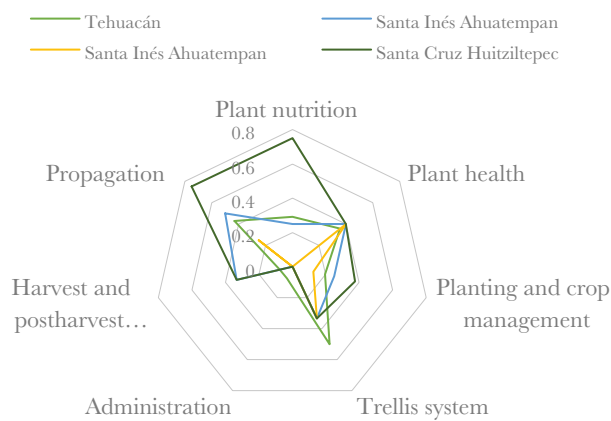


Figure 5. Innovation Adoption Index (InAI) by innovation category of the least outstanding municipalities in dragon fruit (*Hylocereus undatus*) production in the state of Puebla, Mexico.

to improve trellising systems for optimal pruning practices; also for sanitation pruning and pruning to increase number of fruits.

Alongside to the data obtained in the analysis, the surveys applied allowed us obtaining comments from producers that suggest apathy towards receiving technical knowledge that would support them in the development of the innovation categories determined in this analysis as keys for the development of crop yield. These issues on attitudes are important, since failures in technical knowledge tend to limit the appropriate adoption of the innovations.

CONCLUSIONS

The results indicate that dragon fruit yield among the interviewed producers does not depend solely on the number of innovations adopted. Since adopting innovative practices alone does not guarantee an increased yield. Moreover, type of innovation and proper implementation were the determining factors.

Innovations with the greatest impact are those that focused on key aspects such as crop nutrition, pest & disease control practices, and improvement of trellising systems; these aspects directly affect production efficiency and sustainability of this agricultural crop.

REFERENCES

- ASERCA. Apoyos y Servicios a la Comercialización Agropecuaria (2000). *Revista Claridades Agropecuarias* 82. Retrieved: June 2000.
- Goodman, L. A. (1961) Snowball Sampling. *Annals of Mathematical Statistics*, 32, 148-170. <https://doi.org/10.1214/aoms/1177705148>
- INIFAP. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (2023). La pitahaya: un cultivo no tradicional con alta demanda. <https://www.gob.mx/inifap/articulos/pitahaya-cultivo-no-tradicional-con-alta-demanda-en-el-mundo>. Retrieved: September 2023.
- Lira, O.S. (2011). Evaluación de materiales orgánicos como fuente de fertilización para la pitahaya (*Hylocereus* spp). <https://api.semanticscholar.org/CorpusID:82530158>. Retrieved: December 2022.
- Meraz-Alvarado, M. R., Gómez-Cruz, M. A., & Schwentesius-Rindermann, R. R. (2003). Pitahaya de México-Producción y Comercialización en el Contexto Internacional. In: Flores V., C. A. (ed.). *Pitayas y Pitahayas*. CIESTAAM-Universidad Autónoma Chapingo (pp: 99-116). <https://repositorio.chapingo.edu.mx/bitstreams/3b68b5de-3365-41dc-982a-f6cdc18d5d3c/download>. Retrieved: July 2022.
- Muñoz R., M., & Santoyo C., V.H. (2011). La Red de Valor - herramienta de análisis para la toma de decisiones de política pública y estrategia agroempresarial. Nota de investigación. <https://www.studocu.com/es-mx/document/universidad-autonoma-chapingo/> Document search: 22207850
- Muñoz, R. M., Aguilar, Á. J., Rendón, M. R., & Altamirano, C. J. R. (2007). Análisis de la dinámica de innovación en cadenas agroalimentarias. Universidad Autónoma Chapingo-CIESTAAM. México. https://ciestaam.edu.mx/material_de_divulgacion/analisis-la-dinamica-innovacion-en-cadenas-agroalimentarias/. Retrieved: December 2022.
- Nerd, A., Sitrit, Y., Kaushik, R. A., & Mizrahi, Y. (2002). High summer temperatures inhibit flowering in vine pitaya crops (*Hylocereus* spp.). *Scientia Horticulturae*, 96, 343-350. [https://doi.org/10.1016/S0304-4238\(02\)00093-6](https://doi.org/10.1016/S0304-4238(02)00093-6)
- Ortiz-Hernández, Y. D. (2000). Hacia el conocimiento y conservación de la pitahaya (*Hylocereus* spp.). IPN. <https://books.google.com.mx/books?id=geeArgEACAAJ>. Retrieved: June 2023.
- Ramírez, F. (2007). Manual para la producción y paquete tecnológico de Pitahaya en el Estado de Puebla. Secretaría de Desarrollo Rural del Estado de Puebla. México.
- Santacruz-Vázquez, C., Santacruz-Vázquez, V., & Huerta-Espinosa, V. M. (2009). Agro industrialización de la Pitaya. Habana: Universitaria. <https://www.studocu.com/cl/document/universidad-de-la-habana/quimica/agroindustrializacion-de-pitaya-santacruz-vazquez-claudia/11512765>. Retrieved: May 2023.
- SIACON (Sistema de Información Agroalimentaria de Consulta) (2023). Pitahaya (*Hylocereus undatus*). <https://www.gob.mx/siap/documentos/siacon-ng-161430>. Retrieved: October 2022.

- USDA-United States Department of Agriculture. (2022). World Crops Database. <https://fdc.nal.usda.gov/>. Retrieved: May 2022.
- Valiente-Banuet, A., R. Santos, M. C. Arizmendi and A. Casas. (2007). Pollination biology of the hemiepiphytic cactus *Hylocereus undatus* in the Tehuacan Valley, México. *Journal of arid Environments* 68: 1-8.



Firmness and antioxidant compound changes in avocado (*Persea americana* Mill.) pulp during ripening at different storage temperatures

Nallely Rosas-Flores¹; Saucedo-Veloz, Crescenciano²; López-Jiménez, Alfredo^{2*}; Saucedo-Reyes, Daniela²; Valle-Guadarrama, Salvador³; Loera-Alvarado, Gerardo⁴

¹ Tecnológico de Estudios Superiores de Chicoloapan. División de Ingeniería en Desarrollo Comunitario. Camino al Monte s/n col. Loma de Guadalupe, Chicoloapan de Juárez, Estado de México, México. C.P. 56380.

² Colegio de Postgraduados. Campus Montecillo. Recursos Genéticos y Productividad-Fruticultura. Carretera México-Texcoco km 36.5, Estado de México, México. C.P. 56264.

³ Universidad Autónoma Chapingo. Ingeniería Agroindustrial. Carretera México-Texcoco km 38.5, Chapingo, Texcoco, Estado de México, México. C.P. 56264.

⁴ Colegio de Postgraduados, Campus San Luis Potosí. Iturbide 73, Salinas de Hidalgo., San Luis Potosí, México. C.P. 78600.

* Correspondence: lopezja@colpos.mx

Citation: Rosas-Flores, N., Saucedo-Veloz, C., López-Jiménez, A., Saucedo-Reyes, D., Valle-Guadarrama, S., & Loera-Alvarado, D. (2026). Firmness and antioxidant compound changes in avocado (*Persea americana* Mill.) pulp during ripening at different storage temperatures. *Agro Productividad*. <https://doi.org/10.32854/1jnde665>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: August 8, 2025.

Accepted: January 24, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 123-136.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



ABSTRACT

Objective: To evaluate changes in firmness, total phenol content, chlorophylls, carotenoid profile and antioxidant capacity in the pulp of two avocado cultivars and one genotype at different storage temperatures.

Design/methodology/approach: Avocado fruits were divided into two groups. One group of avocado fruit was stored at 20 °C for eight days, while the second group was stored at 2 °C for 21 days, followed by two additional days at 20 °C to allow ripening. Firmness, total phenols, antioxidant capacity, pigments, and carotenoid profile were determined in the pulp after the storage period.

Results: Avocado fruit on cold storage continued the normal ripening process; however, quality deterioration occurred more rapidly than in fruit stored at 20 °C.

Findings/conclusions: During cold storage, flesh firmness of the cultivars (Colín V33 and Hass) and genotype (Oaxaca-7) was not affected. However, once they were transferred to ripening temperature (20 °C), their shelf life was reduced to two days, leading to a rapid deterioration of pulp quality. This deterioration occurred because the contents of phenols, chlorophylls, and carotenoids decreased significantly, thereby affecting the antioxidant activity of the avocado fruits under study, as well as the nutraceutical value provided by chlorophylls and carotenoids, specifically lutein.

Keywords: *Persea americana* Mill., carotenoids, antioxidant capacity, firmness, total phenol content.

INTRODUCTION

Chilling injury in avocado fruits is one of the main problems associated with storage under refrigeration conditions. It is characterized by epicarp spotting, pulp browning, and abnormalities in the ripening process when fruits are exposed to critical temperatures that

induce these physiological alterations (Wang *et al.*, 2012). The response to refrigeration temperatures may differ among cultivars and genotypes due to antioxidant capacity, which is determined by the content of phenolic compounds and carotenoids (Bertiling *et al.*, 2007; Lu *et al.*, 2009).

Phenolic compounds are produced during the secondary metabolism of plants and are associated with the color, flavor, and antioxidant capacity of horticultural products (Sultana and Anwar, 2008). They occur in a wide range of structures, either as free phenolic acids or bound to other molecules such as sugars, or they may be polymerized into more complex structures, including flavonoids, anthocyanins, tannins, and lignins. Furthermore, due to their antioxidant capacity and their relationship with human health, phenolic compounds are considered nutraceutical compounds (Naczka and Shahidi, 2006). Carotenoids are natural pigments that perform essential functions and provide important nutritional benefits to human health, especially α - and β -carotenes and β -cryptoxanthin, which are precursors of vitamin A, retinol, and retinoic acid (Fraser and Bramley, 2004; Krinsky *et al.*, 1994). In plants, carotenoids regulate photosynthesis and prevent photooxidative damage by scavenging free radicals and quenching harmful triplet chlorophyll molecules, thereby inhibiting the generation of singlet oxygen, which limits damage to membranes and proteins (DellaPenna and Pogson, 2006). The presence of carotenoids in fruits provides protection against adverse environmental conditions caused by temperature (high or low), by conferring stability to membrane lipids. In addition, their antioxidant capacity exerts a protective effect on fruit tissues against different types of stress (Lado *et al.*, 2016a). In various fruits, during the ripening process, the content and composition of carotenoids in the pulp and peel are modified, depending on the species, cultivar, and postharvest handling conditions (Alqu  zar *et al.*, 2008; Lado *et al.*, 2016b).

In postharvest conditions, during cold storage, avocado fruit may exhibit sensitivity to chilling injury due to its tropical and subtropical origin. Such damage is mainly manifested by different types of pulp discoloration, including internal browning and darkening of vascular bundles (Whiley *et al.*, 2002). However, susceptibility to chilling injury depends on the cultivar, tissue type, structural components, bioactive compound content, production technology, and postharvest handling, among other factors (Wang *et al.*, 2010). In avocado pulp, the carotenoids present in the highest proportion include lutein, neoxanthin, and β -carotene, which contribute to the protective system by scavenging reactive oxygen species (ROS) generated as a secondary response to chilling injury (Lado *et al.*, 2016a). The objective of this research was to determine changes in firmness, total phenolic content, chlorophylls, carotenoid profile, and antioxidant capacity in the pulp of two avocado cultivars and one genotype stored at different temperatures.

MATERIALS AND METHODS

Plant material

Fruits from two avocado cultivars (*Persea americana* Mill.), Hass ($35.24 \pm 0.62\%$ dry matter) and Col  n V-33 ($34.10 \pm 0.46\%$ dry matter), as well as from the genotype identified as Oaxaca-7 ($26.89 \pm 0.44\%$ dry matter), were harvested at the ‘‘La Cruz’’ Experimental Center, belonging to the Salvador S  nchez Col  n Foundation (CICTAMEX, S. C.), located

in the municipality of Coatepec Harinas, State of Mexico, Mexico, between 18° 48' and 19° 05' N latitude and 99° 43' and 99° 54' W longitude, at an altitude of 2,260 m.

Treatments

One group of fruits was stored at 20 ± 2 °C to allow ripening, while another group was kept under cold storage (2 ± 1 °C) for 21 days and subsequently transferred to 20 ± 2 °C. Fruits directly exposed to ripening conditions were analyzed one day after harvest and after eight days of storage. Fruits stored under refrigeration temperature were analyzed at the end of the cold storage period and after two days of exposure to 20 ± 2 °C.

Response variables

Pulp firmness, total phenolic content, total chlorophyll and carotenoid content, antioxidant capacity, and carotenoid profile were evaluated. Pulp firmness (N) was measured using a Chatillon texture analyzer equipped with a Wagner Force Five sensor model FDV-30, and a 7-mm conical probe. For this purpose, the peel was removed from the equatorial region of the fruit, and the force required to penetrate the pulp was determined.

For the quantification of total phenols, extraction was performed using 500 mg of freeze-dried pulp, to which 10 mL of a methanol-water solution (8:2, v/v) was added. Each sample was then allowed to stand for 24 h at 4 °C. Total phenolic content was determined according to the method proposed by Pío-León *et al.* (2012), with some modifications. Briefly, to a 200- μ L aliquot of each extract, the following reagents were added in order: 2.5 mL of distilled water, 100 μ L of Folin-Ciocalteu reagent diluted with water (1:1, v/v), and 200 μ L of Na₂CO₃ solution in water (2:8, w/v). Subsequently, samples were incubated in the dark for 30 min, and absorbance was measured at 765 nm using a digital spectrophotometer (GENESYS 10V, Thermo Electron Corporation). Results were obtained using a calibration curve and expressed as mg of gallic acid per 100 g of dry weight (mg GA 100 g⁻¹ DW).

For pigment extraction (chlorophylls and total carotenoids), the methodology proposed by Rodrigo *et al.* (2004) was followed with some modifications. Briefly, 600-700 mg of freeze-dried pulp was mixed with 3.0 mL of Milli-Q water and allowed to stand for 10 min. Subsequently, 4.0 mL of methanol and 8.0 mL of dichloromethane were added. The mixture was vortexed for a few seconds and then placed in an ultrasonic bath for 5 min at room temperature. Afterwards, samples were centrifuged at 4,500 rpm for 10 min at 4 °C to separate the liquid and solid phases. The lower phase (organic phase) was recovered, and the addition of dichloromethane was repeated until complete discoloration was achieved. Finally, dichloromethane was evaporated using a rotary evaporator (water bath at 30 °C), obtaining the chlorophyll and carotenoid concentrate (dry sample).

Chlorophyll content (a, b, and total) was quantified according to the method proposed by Rodrigo *et al.* (2004). For this purpose, an aliquot of the dried extract was dissolved in 0.5 mL of dichloromethane, 300 μ L of acetone, and 4.2 mL of a petroleum ether-ethyl ether solution in a 9:1 (v/v) ratio (solution A). The mixture was then vortexed and brought to a known final volume. Absorbance measurements were subsequently performed using a spectrophotometer (Thermo Scientific Multiskan Spectrum) at 644, 662, and 760 nm,

respectively. Results were expressed as $\mu\text{g g}^{-1}$ dry weight ($\mu\text{g g}^{-1}$ DW). Subsequently, the extract was concentrated using a rotary evaporator at 30 °C to determine total carotenoid content, following the method proposed by Rodrigo *et al.* (2003) with some modifications. Briefly, 1.0 mL of dichloromethane and 5.2 mL of methanol were added to the dried sample, and the volume was adjusted to 8.0 mL. Then, 1.0 mL of potassium hydroxide solution (6:4, w/v) was added, the mixture was vigorously shaken, and allowed to stand for 12 h to promote the saponification reaction. Afterwards, 2.0 mL of Milli-Q water and 6.0 mL of solution A were added. The mixture was vortexed vigorously and left to stand. The upper phase was recovered, and the procedure was repeated until the phase became colorless. Finally, the extract was brought to a known final volume with solution A, and absorbance was measured using a spectrophotometer (Thermo Scientific Multiskan Spectrum) at 450 and 540 nm, using an extinction coefficient for β -carotene of $E_{1\%}^{1\text{cm}} = 2500$. Data were expressed as $\mu\text{g } \beta\text{-carotene g}^{-1}$ dry weight ($\mu\text{g } \beta\text{-carotene g}^{-1}$ DW).

For carotenoid profiling, samples were dried under a nitrogen stream, 15 mL of acetone was added, and they were stored at -80 °C for 24 h. Subsequently, samples were centrifuged at 4,500 rpm for 10 min at 4 °C, and the supernatant was recovered. The extract was then evaporated to dryness under an N₂ atmosphere and stored at -20 °C until analysis.

Individual carotenoid composition was analyzed by high-performance liquid chromatography (HPLC) using a Waters liquid chromatography system equipped with a 600E pump, coupled to a photodiode array detector (model 2998) and Empower software (Waters).

A C30 carotenoid column (250×4.6 mm, 5 μm) coupled to a C30 guard column (20×4.0 mm, 5 μm) was used (YMC Europe GmbH). Samples were dissolved in a chloroform:methanol:acetone mixture (3:2:1, v/v/v), and carotenoid separation was performed using an elution gradient composed of methanol (MeOH), water, and methyl tert-butyl ether (MTBE). A chromatogram was obtained for each run, in which carotenoid peaks were identified by their maximum wavelength, and their concentrations were calculated using calibration curves for violaxanthin, neoxanthin, luteoxanthin, lutein, antheraxanthin, β -cryptoxanthin, and α - and β -carotene. Three replicates were performed for each analytical determination. The entire procedure was carried out under dim light conditions to prevent pigment degradation. Concentrations were expressed as $\mu\text{g g}^{-1}$ dry weight ($\mu\text{g g}^{-1}$ DW).

Total antioxidant capacity was determined using the DPPH (2,2-diphenyl-1-picrylhydrazyl) and FRAP (Ferric Reducing Antioxidant Power) methods. For both assays, an extract was prepared from 50 mg of freeze-dried pulp by adding 4 mL of a methanol-water solution (8:2, v/v). The mixture was then centrifuged at 4,500 rpm for 15 min at 4 °C. Subsequently, the supernatant was collected in a graduated tube to quantify the volume and stored at -20 °C until analysis.

For quantification using the DPPH method, the procedure proposed by Brand-Williams *et al.* (1995) was followed with some modifications. Briefly, 3.9 mg of DPPH was dissolved in 100 mL of methanol-water (8:2, v/v). In a polyurethane microplate, 10 μL of the sample extract and 290 μL of the DPPH solution were added. After loading the plate, samples were incubated for 30 min in the dark at room temperature. Absorbance was measured at

512 nm using 300 μL of methanol-water (8:2, v/v) as the blank. A calibration curve was prepared using different concentrations of ascorbic acid, and results were expressed as μg of ascorbic acid per g of pulp on a dry weight basis ($\mu\text{g AAs g}^{-1}\text{ DW}$).

The FRAP assay was based on the methodology developed by Benzie and Strain (1996), with modifications. A 10 mM TPTZ solution (2,4,6-tri(2-pyridyl)-1,3,5-triazine) was prepared according to the following procedure: a 40 mM HCl solution was prepared (1.46 mL of HCl in 1.0 L of water at room temperature), and 0.31 g of TPTZ was dissolved in 100 mL of this solution, heating in a water bath at 50 °C. On the other hand, a 300 mM acetate buffer solution at pH 3.6 was prepared by mixing 3.1 g of sodium acetate and 16 mL of glacial acetic acid in 100 mL of water. In addition, a 20 mM ferric chloride solution was prepared by dissolving 0.135 g in 25 mL of water.

The above solutions were mixed in a 1:10:1 (v/v/v) ratio to form the FRAP reagent, which was placed in a water bath at 37 °C for 10 min. Afterwards, the microplate was loaded by adding 40 μL of the sample extract and 260 μL of the FRAP reagent. Once the plate was prepared, it was incubated for 30 min in the dark at 37 °C. Absorbance was measured at 570 nm, using methanol-water (80:20, v/v) as the blank. Results were obtained from a calibration curve and expressed as μg of ascorbic acid per g of pulp on a dry weight basis ($\mu\text{g AAs g}^{-1}\text{ DW}$).

Data analysis

Data were analyzed using analysis of variance (ANOVA) under a completely randomized design, and mean comparisons were performed using Tukey's test ($\alpha=0.05$). The analysis was conducted using the statistical package SAS System for Windows version 9.0. Each fruit was considered an experimental unit, and three replicates were performed for all variables.

RESULTS AND DISCUSSION

After eight days of storage at 20 ± 2 °C, a significant difference ($p<0.05$) was found in the pulp firmness of the avocado fruits studied compared with the initial condition (Table 1), with a firmness loss greater than 93% in the three evaluated materials. Likewise, a significant difference ($p<0.05$) was observed in the firmness of fruits from the Hass and Colín V33 cultivars stored under refrigeration conditions, showing a decrease of approximately 30% after removal from storage. However, after two days under ripening conditions, a firmness loss greater than 94% was observed in both cultivars. In contrast, firmness in the Oaxaca-7 genotype showed a reduction of 93.5% at the end of cold storage and 95.9% after two days of ripening (Table 2).

The loss of firmness reflected the typical softening of avocado pulp associated with the progression of fruit ripening. This process is related to modifications in the chemical structure of the polymers that make up the cell wall, mainly pectic substances and cellulose, which are degraded due to increased activity of the enzymes pectin methylesterase, polygalacturonase, and cellulases (Arévalo-Galarza *et al.*, 2002; Blakey *et al.*, 2014). The pattern of firmness loss during ripening suggests that this process in fruits exposed to refrigeration conditions proceeded normally with respect to this variable.

Table 1. Changes in firmness, total phenolic content, and antioxidant capacity (DPPH and FRAP) in the pulp of avocado fruits (*Persea americana* Mill.) stored at 20±1 °C for eight days.

Variable	Cultivar	0 days	8 days
Firmness (N)	Hass	29.12±2.07 ^a	0.79±0.17 ^b
	Colín V-33	23.85±2.66 ^a	0.29±0.08 ^b
	Oaxaca-7*	16.54±0.53 ^a	1.00±0.28 ^b
Total phenolic content (GA mg g ⁻¹ DW)	Hass	1040.72±125.15 ^b	3313.33±171.59 ^a
	Colín V-33	1238.86±58.87 ^a	1098.73±63.08 ^b
	Oaxaca-7	1099.08±61.82 ^b	1331.44±126.35 ^a
DPPH antioxidant capacity (AA µg g ⁻¹ DW)	Hass	1350.71±19.18 ^b	2736.26±72.68 ^a
	Colín V-33	694.39±70.35 ^a	753.58±16.2 ^a
	Oaxaca-7	1341.24±80.59 ^b	1798.30±83.04 ^a
Ferric Reducing Antioxidant Power (µg AAs g ⁻¹ DW)	Hass	375.25±6.22 ^b	656.61±31.13 ^a
	Colín V-33	698.61±19.98 ^a	498.91±11.47 ^b
	Oaxaca-7	876.97±12.47 ^a	813.97±21.36 ^b

*Genotype. DW: dry weight; DPPH: 2,2-diphenyl-1-picrylhydrazyl; FRAP: Ferric Reducing Antioxidant Power; AA: ascorbic acid. Means followed by the same letter within each row are not significantly different (α=0.05). Values are presented as mean±SD, n=3.

Table 2. Changes in firmness, total phenolic content, and antioxidant capacity (DPPH and FRAP) in the pulp of avocado fruits (*Persea americana* Mill.) stored at 2±1 °C for 21 days, followed by two days at 20±2 °C.

Variable	Cultivar	Storage/ripening time		
		0 days	21 days	23 days
Firmness (N)	Hass	29.12±2.07 ^a	19.68±1.21 ^b	1.65±0.49 ^c
	Colín V-33	23.85±2.67 ^a	16.85±1.99 ^b	0.98±0.16 ^c
	Oaxaca-7*	16.54±0.53 ^a	1.06±0.51 ^b	0.67±0.12 ^b
Total phenolic content (GA mg g ⁻¹ DW)	Hass	1040.72±125.16 ^c	1384.40±149.91 ^b	1739.65±24.40 ^a
	Colín V-33	1238.86±58.87 ^b	775.66±92.99 ^c	1937.43±23.84 ^a
	Oaxaca-7	1099.08±61.83 ^a	1074.92±49.10 ^a	806.25±67.92 ^b
DPPH antioxidant capacity (AA µg g ⁻¹ DW)	Hass	1267.00±149.82 ^c	3423.40±203.92 ^a	1900.20±171.92 ^b
	Colín V-33	694.39±70.36 ^b	981.94±74.05 ^a	1066.10±20.73 ^a
	Oaxaca-7	1560.40±322.74 ^a	1251.20±203.78 ^a	614.70±22.41 ^b
Ferric Reducing Antioxidant Power (µg AAs g ⁻¹ DW)	Hass	656.62±31.14 ^c	1776.46±59.23 ^a	990.10±115.07 ^b
	Colín V-33	698.61±19.98 ^a	592.65±14.27 ^b	665.92±4.88 ^a
	Oaxaca-7	876.80±12.48 ^a	687.52±23.18 ^b	375.25±6.22 ^c

*Genotype. DW: dry weight; DPPH: 2,2-diphenyl-1-picrylhydrazyl; FRAP: Ferric Reducing Antioxidant Power; AAs: ascorbic acid. Means followed by the same letter within each row are not significantly different (α=0.05). Values are presented as mean±SD, n=3.

A significant difference (p<0.05) was found in the content of phenolic compounds in fruits from the three evaluated materials between the initial condition and after eight days of storage. In the Hass cultivar, total phenolic content tripled, reaching a final concentration of 3313.33 mg GA g⁻¹ DW, whereas in the Oaxaca-7 genotype, an increase of approximately 20% was observed, with a final content of 1331.44 mg GA g⁻¹ DW. In

contrast, the Colín V33 cultivar showed an 11% reduction, ending with 1098.73 mg GA g⁻¹ DW (Table 1).

In the case of fruits stored under refrigeration conditions (21 days at 2±1 °C), a significant difference (p<0.05) was found in the content of phenolic compounds compared with the initial condition. In the Hass cultivar, an increase of 33% was observed at the end of cold storage, followed by a further 67% increase during ripening (two days at 20±2 °C), reaching a final concentration of 1739.65 mg GA g⁻¹ DW. In the Colín V33 cultivar, a 37% decrease was observed at the end of storage, followed by a subsequent 56% increase during ripening, with a final concentration of 1937.43 mg GA g⁻¹ DW. Meanwhile, phenolic compound content in the Oaxaca-7 genotype remained unchanged during refrigerated storage; however, after ripening, a 26% reduction was observed, resulting in a final content of 806.25 mg GA g⁻¹ DW (Table 2). Phenolic compounds are responsible for the highest antioxidant activity in horticultural products (Heim *et al.*, 2002). According to the results obtained using the DPPH (2,2-diphenyl-1-picrylhydrazyl) method in fruits directly exposed to ripening temperature, a significant increase (p<0.05) was found only in the Hass cultivar and the Oaxaca-7 genotype, where an increase of slightly more than twofold and 34%, respectively, was observed. In contrast, no significant change was detected in the Colín V33 cultivar (Table 1).

On the other hand, in fruits stored under refrigeration conditions (21 days at 2.0±1.0 °C), a significant difference (p<0.05) was observed both at the end of storage and after ripening compared with the initial condition. In the Hass and Colín V33 cultivars, increases of 170% and 40% were observed at the end of cold storage, respectively; however, during ripening, the increase was close to 50% in both cultivars. Meanwhile, in the Oaxaca-7 genotype, a decrease of 20% was found at the end of storage and of 60% during ripening compared with the initial condition (Table 2).

For the Ferric Reducing Antioxidant Power (FRAP) assay, a significant difference (p<0.05) was found in fruits directly exposed to ripening conditions compared with the initial condition. In the Hass cultivar, an increase of approximately 75% was observed, whereas in the Colín V33 cultivar and the Oaxaca-7 genotype, reductions of 28.58% and 7.18%, respectively, were detected.

In fruits stored under refrigeration conditions (21 days at 2±1 °C) and subsequently ripened (two days at 20±2 °C), a significant difference (p<0.05) was found in FRAP values. Notably, the Hass cultivar showed an increase of 170% at the end of cold storage and a further 50% increase during ripening. In contrast, the Oaxaca-7 genotype exhibited reductions of 21.6% and 57% in FRAP at the end of storage and during ripening, respectively. In the case of the Colín V33 cultivar, a 15% reduction in FRAP was observed at the end of refrigeration storage and remained unchanged during ripening (Table 2). An increase in antioxidant capacity has been reported by Daiuto *et al.* (2011), who stated that antioxidant capacity measured by the DPPH method increased in 'Fuerte' avocado fruits during the ripening process. In this regard, the results obtained in the present study suggest that the differences observed in antioxidant capacity among the fruits evaluated are related to variations in their

phenolic compound profiles. A similar response, in terms of a significant increase in antioxidant capacity, was observed in fruits of the Hass cultivar when measured using the FRAP method.

The results obtained in this study are consistent with those reported by Tomás-Barberán and Espín (2001) regarding the effect of cultivar and/or genetic material on the antioxidant activity of avocado fruits. In addition, no clear relationship was observed between total phenolic content and antioxidant capacity in the cultivars and genotype evaluated. This response agrees with the findings of Daiuto *et al.* (2011), who reported no significant correlation between total phenolic content and antioxidant capacity in 'Fuerte' avocado, suggesting that variations in the content and profile of phenolic compounds present in each genetic material may influence antioxidant behavior.

It is important to note that the higher antioxidant capacity values obtained using the DPPH method, compared with the FRAP method, support the hypothesis that this may be due to the presence of lipophilic compounds, as well as other constituents such as α -tocopherol, carotenoids, chlorophylls, and flavonoids in avocado extracts, which contribute to a greater stabilization of the DPPH free radical (Moreno *et al.*, 2014).

In fruits directly exposed to ripening conditions, a significant difference ($p < 0.05$) was observed in pigment content compared with the initial condition. In the 'Hass' cultivar, a decrease of 43, 50, 29, and 53% was recorded in total chlorophyll, chlorophyll *a*, chlorophyll *b*, and total carotenoids, respectively.

A similar pattern was found in the Colín V33 cultivar, with a 37% reduction in total chlorophyll and a 54% decrease in chlorophyll *a*, whereas chlorophyll *b* and total carotenoids remained unchanged, showing no significant differences.

Table 3. Changes in chlorophyll content (total, *a*, and *b*) and total carotenoids in the pulp of avocado fruits (*Persea americana* Mill.) stored at 20 ± 1 °C for eight days.

Variable	Cultivar	Ripening time	
		0 days	8 days
Total chlorophyll ($\mu\text{g g}^{-1}$ DW)	Hass	103.48 \pm 2.50 ^a	58.55 \pm 6.30 ^b
	Colín V-33	41.48 \pm 2.53 ^a	25.87 \pm 0.97 ^b
	Oaxaca-7*	184.02 \pm 50.39 ^a	116.77 \pm 30.66 ^a
Chlorophyll <i>a</i> ($\mu\text{g g}^{-1}$ DW)	Hass	70.75 \pm 1.56 ^a	35.32 \pm 2.43 ^b
	Colín V-33	33.95 \pm 2.28 ^a	15.64 \pm 0.36 ^b
	Oaxaca-7	119.25 \pm 26.49 ^a	69.54 \pm 13.09 ^b
Chlorophyll <i>b</i> ($\mu\text{g g}^{-1}$ DW)	Hass	32.72 \pm 3.66 ^a	23.23 \pm 3.87 ^b
	Colín V33	7.53 \pm 1.92 ^a	10.22 \pm 1.99 ^a
	Oaxaca-7	64.77 \pm 23.91 ^a	47.22 \pm 17.65 ^a
Total Carotenoid Content (β -carotene $\mu\text{g g}^{-1}$ DW)	Hass	20.41 \pm 2.37 ^a	9.63 \pm 1.66 ^b
	Colín V-33	16.88 \pm 1.39 ^a	14.17 \pm 1.37 ^a
	Oaxaca-7	34.70 \pm 5.3 ^a	16.09 \pm 2.07 ^b

*Genotype. DW: dry weight (g). Means followed by the same letter within each row are not significantly different ($\alpha = 0.05$). Values are expressed as mean \pm SD, $n = 3$.

In contrast, in the Oaxaca-7 genotype, only chlorophyll *a* showed a loss of 40%, while total chlorophyll and chlorophyll *b* remained without significant changes. Additionally, a 54% increase in total carotenoids was observed (Table 3).

In fruits stored under refrigerated conditions, significant differences ($p < 0.05$) were observed in certain cultivars and pigments, either immediately after cold storage or during ripening. In the cultivar *Hass*, at the end of refrigeration, decreases of 15%, 28%, and 48% were recorded in total chlorophyll, chlorophyll *a*, and total carotenoids, respectively, whereas chlorophyll *b* remained constant. However, during ripening, total chlorophyll as well as chlorophyll *a* and *b* declined by approximately 44%, while total carotenoid content showed no significant changes.

In the cultivar Colín V33, a similar behavior was observed at the end of storage; however, the reductions in total chlorophyll, chlorophyll *a*, and total carotenoids were 56%, 74%, and 37%, respectively. During ripening, chlorophyll degradation continued, reaching reductions of up to 75% in total chlorophyll, 81% in chlorophyll *a*, and 46% in chlorophyll *b*, whereas total carotenoids remained unchanged. In the case of the genotype Oaxaca-7, only a 38% loss of chlorophyll *a* and a 55% reduction in total carotenoid content were observed up to the ripening stage. Total chlorophyll and chlorophyll *b* remained unchanged (Table 4).

Pigment content is determined by the plant material and the stage of maturity (Soong and Barlow, 2004), and the metabolism of these compounds directly affects their concentration. In the case of the cultivar *Hass*, Wang *et al.* (2012) reported an increase in phenolic compounds after cold storage for 21 and 35 days, demonstrating that in this cultivar exposure to refrigeration temperatures promotes the accumulation of total phenols. However, according to Di Stefano *et al.* (2017), during avocado fruit ripening

Table 4. Changes in chlorophyll content (total, *a* and *b*) and total carotenoids in the pulp of avocado fruits (*Persea americana* Mill.) stored at 2 ± 1 °C for 21 days, followed by two days at 20 ± 1 °C.

Variable	Cultivar	Storage time + ripening time		
		0 days	21 days	23 days
Total chlorophyll ($\mu\text{g g}^{-1}$ DW)	Hass	103.48 \pm 2.51 ^a	87.44 \pm 5.07 ^b	59.03 \pm 3.51 ^c
	Colín V-33	41.48 \pm 2.54 ^a	18.23 \pm 4.34 ^b	10.44 \pm 0.94 ^c
	Oaxaca-7*	184.03 \pm 50.40 ^a	150.66 \pm 2.19 ^a	124.32 \pm 2.88 ^a
Chlorophyll <i>a</i> ($\mu\text{g g}^{-1}$ DW)	Hass	70.75 \pm 1.57 ^a	50.52 \pm 7.96 ^b	39.08 \pm 1.60 ^c
	Colín V-33	33.95 \pm 2.29 ^a	8.87 \pm 1.34 ^b	6.34 \pm 0.94 ^b
	Oaxaca-7	119.25 \pm 26.50 ^a	83.01 \pm 3.06 ^{ab}	72.81 \pm 0.58 ^b
Chlorophyll <i>b</i> ($\mu\text{g g}^{-1}$ DW)	Hass	32.72 \pm 3.66 ^a	36.92 \pm 2.90 ^a	18.75 \pm 0.70 ^b
	Colín V-33	7.53 \pm 1.92 ^{ab}	9.35 \pm 3.04 ^a	4.09 \pm 0.23 ^b
	Oaxaca-7	64.77 \pm 23.91 ^a	67.65 \pm 0.98 ^a	31.51 \pm 3.21 ^a
Total carotenoid content (β -carotene $\mu\text{g g}^{-1}$ DW)	Hass	20.41 \pm 2.38 ^a	10.55 \pm 1.77 ^b	11.35 \pm 3.99 ^b
	Colín V-33	16.88 \pm 1.39 ^{ab}	10.65 \pm 0.84 ^b	19.34 \pm 5.36 ^a
	Oaxaca-7	34.70 \pm 5.36 ^a	27.38 \pm 6.11 ^{ab}	15.54 \pm 5.30 ^b

*Genotype. DW: dry weight (g). Means followed by the same letter within each row are not significantly different ($\alpha = 0.05$). Values are expressed as mean \pm SD, n=3.

there are differences among cultivars in both the profile and type of phenolic compounds, which explains the contrasting patterns observed in the total phenol content of the fruits evaluated in this study. In other studies (Ashton *et al.*, 2006; Cox *et al.*, 2004), a decrease in chlorophyll concentration has been observed in 'Hass' avocado fruits as a result of the ripening process. These authors also reported high concentrations of chlorophyll *a* and low levels of chlorophyll *b*, as was likewise found in the present study. Regarding total carotenoids, exposure to refrigeration conditions did not affect the normal carotenoid metabolism associated with ripening in the genotype and the cultivar *Hass*. It has been noted that factors such as harvest season, agroclimatic conditions, and production technology significantly influence carotenoid synthesis in avocado fruits. Furthermore, during the ripening process, these pigments tend to decrease, as has been reported by several researchers (Ashton *et al.*, 2006; Lu *et al.*, 2009).

With regard to the carotenoid profile, lutein was the most abundant carotenoid in the pulp of avocado fruits from both cultivars and the genotype. At harvest, lutein concentrations of $1.19 \mu\text{g g}^{-1}$ DW were detected in the cultivar Colín V33, $12.61 \mu\text{g g}^{-1}$ DW in the genotype, and $2.65 \mu\text{g g}^{-1}$ DW in the cultivar *Hass*. At the edible ripeness stage, the content of this carotenoid decreased to $0.59 \mu\text{g g}^{-1}$ DW in Colín V33, $5.00 \mu\text{g g}^{-1}$ DW in the genotype, and $1.81 \mu\text{g g}^{-1}$ DW in *Hass* (Figure 1), representing reductions of 50.4%, 60.3%, and 31.7%, respectively.

Other carotenoids were also detected in relevant amounts, including neoxanthin, trans-violaxanthin, 9-cis-neoxanthin, luteoxanthin, cis-violaxanthin, antheraxanthin, β -cryptoxanthin, α -carotene, and β -carotene; however, all were present at concentrations below $1.00 \mu\text{g g}^{-1}$ DW.

After 21 days of storage at 2 ± 1 °C, carotenoid concentrations decreased, even after transfer to ripening temperature. In this regard, lutein declined to $0.65 \mu\text{g g}^{-1}$ DW in the cultivar Colín V33, $5.56 \mu\text{g g}^{-1}$ DW in the genotype, and $2.33 \mu\text{g g}^{-1}$ DW in the cultivar *Hass*, corresponding to reductions of 45.8%, 55.9%, and 12.1%, respectively, relative to the values at harvest.

It is noteworthy that changes were also observed in the relative abundance of the other detected carotenoids. Thus, in the genotype, after 8 days of ripening at 20 ± 2 °C, the concentration order from highest to lowest was lutein, neoxanthin, and cis-violaxanthin. However, after 21 days at 2 ± 1 °C followed by 2 days at 20 ± 2 °C, the order shifted to neoxanthin, lutein, and cis-violaxanthin.

Lutein is a carotenoid typically found in green tissues and was detected in the highest abundance in the pulp of avocado fruits; its concentration decreases during the ripening process (Ashton *et al.*, 2006; Lado *et al.*, 2017), showing a pattern similar to that observed in the present study. Other researchers have also reported the presence of zeaxanthin, β -cryptoxanthin, α -carotene, and β -carotene in avocado pulp (Lu *et al.*, 2009). Lutein and zeaxanthin have been associated with a lower incidence of ocular diseases such as cataracts and age-related macular degeneration. They also function as antioxidants, protecting against the formation of reactive oxygen species. On the other hand, β -cryptoxanthin, α -carotene, and β -carotene exhibit provitamin A activity. Additionally, these compounds may exert other health-related functions of importance in humans, such as enhancing the

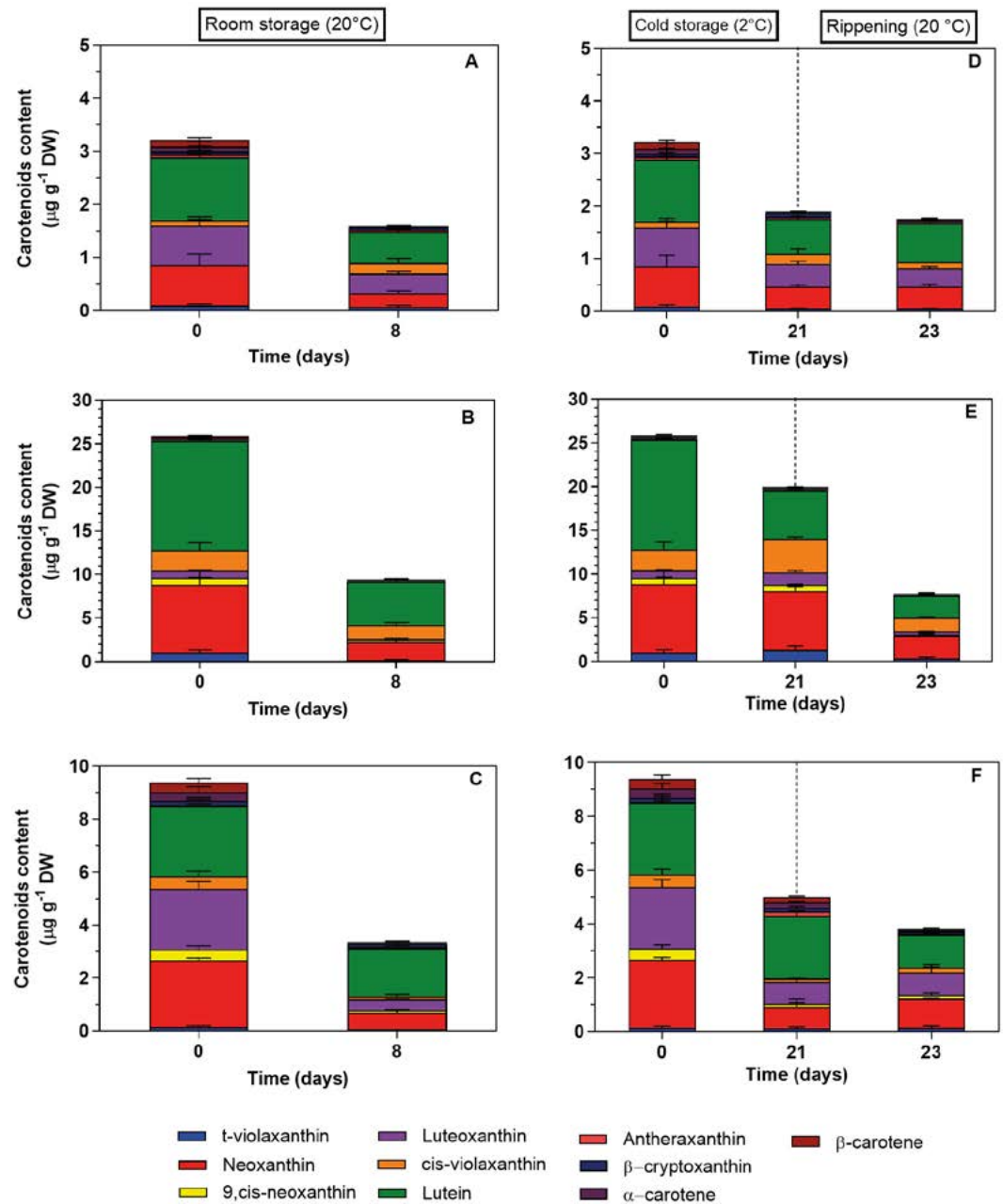


Figure 1. Carotenoid behavior in the pulp of avocado fruits from *Hass* (C, F), Colón V-33 (A, D), and Oaxaca-7 (B, E) stored at 20 ± 1 °C, and stored at 2 ± 1 °C for 21 days followed by 2 days at 20 ± 1 °C. Carotenoid data are presented as mean \pm SD. Source: Author’s own elaboration based on experimental data.

immune system and providing photoprotection to tissues, including epithelial and ocular tissues (Beltrán *et al.*, 2012; Olmedilla-Alonso and Estévez-Santiago, 2017; Rodríguez-Concepcion *et al.*, 2018). It has also been reported that the carotenoid profile is modified in response to developmental stage, variety or cultivar, harvest date, production technologies, environmental conditions, and postharvest handling. Under normal light conditions, higher concentrations of lutein, β -carotene, violaxanthin, and neoxanthin are typically found in

green plant tissues, whereas zeaxanthin, α -carotene, β -cryptoxanthin, and antheraxanthin occur at lower levels.

The results obtained in the present study highlight the effect of cultivar and genotype on the carotenoid content, concentration dynamics, and profile, as well as the influence of maturity stage and storage conditions. These factors ultimately translate into differences in pulp color and the nutraceutical value of avocado fruits (Rodríguez-Concepcion *et al.*, 2018).

CONCLUSIONS

During cold storage, fruit quality was not affected in the cultivars (Colín V33 and Hass) and the genotype (Oaxaca-7). However, once the fruits were transferred to ripening temperature (20 °C), their shelf life was reduced to only two days, and pulp quality deteriorated rapidly. This decline was associated with a significant decrease in phenols, chlorophylls, and carotenoids, which negatively affected the antioxidant activity of the avocado fruits under study, as well as the nutraceutical value provided by chlorophyll and carotenoid contents, particularly lutein.

REFERENCES

1. Wang, M., Zheng, Y., Khuong, T. & Lovatt C. J. (2012). Effect of harvest date on the nutritional quality and antioxidant capacity in 'Hass' avocado during storage. *Food Chemistry*, 135(2), 694-698. doi: <https://doi.org/10.1016/j.foodchem.2012.05.022>
2. Bertling, I., Tesfay, S. Z. & Bower, J. P. (2007) Antioxidants in 'Hass' avocado. *South African Avocado Growers' Association Yearbook*, 30, 17-19. Recuperado de: https://www.avocadosource.com/Journals/SAAGA/SAAGA_2007/SAAGA_2007_V30_PGS_17-19_Bertling.pdf
3. Lu, Q. Y., Zhang, Y., Wang, Y., Wang, D., Lee, R. P., Gao, K., Byrns, R. & Heber, D. (2009). California Hass Avocado: Profiling of Carotenoids, Tocopherol, Fatty Acid, and Fat Content During Maturation and from Different Growing Areas. *Journal of Agricultural and Food Chemistry*, 57(21), 10408-10413. doi: <https://doi.org/10.1021/jf901839h>
4. Sultana, B. & Anwar, F. (2008). Flavonols (kaempferol, quercetin, myricetin) contents of selected fruits, vegetables and medicinal plants. *Food Chemistry*, 108(3), 879-884. doi: <https://doi.org/10.1016/j.foodchem.2007.11.053>
5. Naczki, M. & Shahidi, F. (2006). Phenolics in cereals, fruits and vegetables: occurrence, extraction and analysis. *Journal of pharmaceutical and biomedical analysis*, 41(5), 1523-1542. doi: <https://doi.org/10.1016/j.jpba.2006.04.002>
6. Fraser, P. D. & Bramley, P. M. (2004). The biosynthesis and nutritional uses of carotenoids. *Progress in Lipid Research*, 43(3), 228-265. doi: <https://doi.org/10.1016/j.plipres.2003.10.002>
7. Krinsky, N. I. (1994). The biological properties of carotenoids. *Pure and Applied Chemistry*, 66(5), 1003-101.
8. DellaPenna, D. & Pogson, B. J. (2006). Vitamin synthesis in plants: tocopherols and carotenoids. *Annual Review of Plant Biology*, 57(1), 711-738. doi: <https://doi.org/10.1146/annurev.arplant.56.032604.144301>
9. Lado, J., Zacarías, L. & Rodrigo, M. J. (2016a). Regulation of Carotenoid Biosynthesis During Fruit Development. En C. Stange (Ed.), *Carotenoids in Nature: Biosynthesis, Regulation and Function* (pp. 161-198). Switzerland: Springer International Publishing. doi: https://doi.org/10.1007/978-3-319-39126-7_6
10. Alquézar, B., Rodrigo, M. J. & Zacarías, L. (2008). Carotenoid biosynthesis and their regulation in Citrus fruits. *Tree Forestry Science Biotechnology*, 2(1), 23-35. Recuperado de: <https://www.1stfruits.co.za/wp/wp-content/uploads/2022/05/Carotenoid-Biosynthesis.pdf>
11. Lado, J., Rodrigo, M. J., López-Climent, M., Gómez-Cadenas, A. & Zacarías, L. (2016b). Implication of the antioxidant system in chilling injury tolerance in the red peel of grapefruit. *Postharvest Biology and Technology*, 111, 214-223. doi: <https://doi.org/10.1016/j.postharvbio.2015.09.013>
12. Whiley, A. W., Schaffer, B. & Wolstenholme, B. N. (2002). *The Avocado: Botany, Production and Uses*. Wallingford, U.K.: CABI Publishing.

13. Wang, W., Bostic, T. R. & Gu, L. (2010). Antioxidant capacities procyanidins and pigments in avocados of different strains and cultivars. *Food Chemistry*, 122(4), 1193-1198. doi: <https://doi.org/10.1016/j.foodchem.2010.03.114>
14. Pío-León, J. F., Díaz-Camacho, S. P., Montes-Avila, J., López-Angulo, G. & Delgado-Vargas, F. (2012). Nutritional and nutraceutical characteristics of white and red *Pithecellobium dulce* (Roxb.) Benth fruits. *Fruits*, 68(5), 397-408. doi: <https://doi.org/10.1051/fruits/2013084>
15. Rodrigo, M. J., Marcos, J. F. & Zacarías, L. (2004). Biochemical and Molecular Analysis of Carotenoid Biosynthesis in Flavedo of Orange (*Citrus sinensis* L.) during Fruit Development and Maturation. *Journal of Agricultural and Food Chemistry*, 52, 6724-6731. doi: <https://doi.org/10.1021/jf049607f>
16. Rodrigo, M. J., Marcos, J. A., Alférez, F., Mallent, M. D. & Zacarías, L. (2003). Characterization of Pinalate, a novel *Citrus sinensis* mutant with a fruit-specific alteration that results in yellow pigmentation and decreased ABA content. *Journal of Experimental Botany*, 54(383), 727-738. doi: <https://doi.org/10.1093/jxb/erg083>
17. Brand-Williams, W., Cuvelier, M. E. & Berset, C. (1995). Use of a Free Radical Method to Evaluate Antioxidant Activity. *Food Science and Technology*, 28(1), 25-30. doi: [https://doi.org/10.1016/S0023-6438\(95\)80008-5](https://doi.org/10.1016/S0023-6438(95)80008-5)
18. Benzie, F. F. I. & Strain, J. J. (1996). The Ferric Reducing Ability of Plasma (FRAP) as a Measure of "Antioxidant Power": The FRAP Assay. *Analytical Biochemistry*, 239, 70-76. doi: <https://doi.org/10.1006/abio.1996.0292>
19. Arévalo-Galarza, L., Saucedo-Veloz, C., Bustos-Ramírez, E. & González-Hernández, H. (2002). Maduración de frutos de aguacate 'Hass' tratados con radiación gamma. *Agrociencia*, 36, 667-673. Recuperado de: <https://www.redalyc.org/pdf/302/30236604.pdf>
20. Blakey, R. J., Tesfay, S. Z., Bertling, I. & Bower, J. P. (2014). Ripening physiology and quality of 'Hass' avocado (*Persea americana* Mill.) after cold storage at 1 °C. *The Journal of Horticultural Science and Biotechnology*, 89(6), 655-662. doi: <https://doi.org/10.1080/14620316.2014.11513134>
21. Heim, E. K., Tagliaferro, R. A. & Bobilya, J. D. (2002). Flavonoid antioxidants: chemistry, metabolism and structure-activity relationships. *The Journal of Nutritional Biochemistry*, 13, 572-584. doi: [https://doi.org/10.1016/S0955-2863\(02\)00208-5](https://doi.org/10.1016/S0955-2863(02)00208-5)
22. Daiuto, E. R., Fumes, J. G. F., Vieites, R. L., Cabia, N. C. & Castro R. S. D. (2011). Antioxidant capacity and total phenolic content of hydrothermally-treated 'Fuerte' avocado. *Advances in Horticultural Science*, 25(2), 75-80. doi: <https://doi.org/10.13128/ahs-12771>
23. Tomás Barberán, F. A. & Espín, J. C. (2001). Phenolic compounds and related enzymes as determinants of quality in fruits and vegetables. *Journal of the Science of Food and Agriculture*, 81(9), 853-876. doi: <https://doi.org/10.1002/jsfa.885>
24. Moreno, E., Ortiz, B. L. & Restrepo, L. P. (2014). Contenido total de fenoles y actividad antioxidante de pulpa de seis frutas tropicales. *Revista Colombiana de Química*, 43(3), 41-48. Recuperado de: <http://www.scielo.org.co/pdf/rcq/v43n3/v43n3a06.pdf>
25. Soong, Y. Y. & Barlow, P. J. (2004). Antioxidant activity and phenolic content of selected fruit seeds. *Food Chemistry*, 88(3), 411-417. doi: <https://doi.org/10.1016/j.foodchem.2004.02.003>
26. Di Stefano, V., Avellone, G., Bongiorno, D., Indelicato, S., Massenti, R. & Lo Bianco, R. (2017). Quantitative evaluation of the phenolic profile in fruits of six avocado (*Persea americana*) cultivars by ultra-high-performance liquid chromatography-heated electrospray-mass spectrometry. *International Journal of Food Properties*, 20(6), 1302-1312. doi: <https://doi.org/10.1080/10942912.2016.1208225>
27. Ashton, O. B. O., Wong, M., McGhie, T. K., Vather, R., Wang, Y., Requejo-Jackman, C., Ramankutty, P. & Woolf, A. B. (2006). Pigments in Avocado Tissue and Oil. *Journal of Agricultural and Food Chemistry*, 54(26), 10151-10158. doi: <https://doi.org/10.1021/jf061809j>
28. Cox, A. K., McGhie, T. K., White, A. & Woolf, A. B. (2004). Skin colour and pigment changes during ripening of 'Hass' avocado fruit. *Postharvest Biology and Technology*, 31(3), 287-294. doi: <https://doi.org/10.1016/j.postharvbio.2003.09.008>
29. Lado, J., Cuéllar, F. A., Zacarías, L. & Rodrigo, M. J. (2017). Carotenoides en frutos cítricos: diversidad y biosíntesis, En A. J. Meléndez-Martínez (Ed.), Carotenoides en agroalimentación y salud (pp. 223-246). Sevilla, España: Editorial Terracota. Recuperado de: <http://hdl.handle.net/10261/158244>
30. Beltrán, B., Estévez, R., Cuadrado, C., Jiménez, S. & Olmedilla-Alonso, B. (2012). Base de datos de carotenoides para valoración de la ingesta dietética de carotenos, xantofilas y de vitamina A; utilización en un estudio comparativo del estado nutricional en vitamina A de adultos jóvenes. *Nutrición Hospitalaria*, 27(4), 1334-1343. doi: <https://doi.org/10.3305/nh.2012.27.4.5886>

31. Olmedilla-Alonso, B. & Estévez-Santiago, R. (2017) Estimación de la ingesta de carotenoides en la dieta, En A. J. Meléndez-Martínez (Ed.), *Carotenoides en agroalimentación y salud* (pp.430-443). Sevilla, España: Editorial Terracota. Recuperado de: <http://hdl.handle.net/10261/158244>
32. Rodríguez-Concepcion, M., Avalos, J., Bonet, M. L., Boronat, A., Gomez-Gomez, L., Hornero-Mendez, D., Limon, M. C., Meléndez-Martínez, J. A., Olmedilla-Alonso, B., Palou, A., Ribot, J., Rodrigo, M. J., Zacarias, L. & Zhu, C. (2018). A global perspective on carotenoids: Metabolism, biotechnology, and benefits for nutrition and health. *Progress in Lipid Research*, 70, 62-93. doi: <https://doi.org/10.1016/j.plipres.2018.04.004>



Economics of Animal Welfare: opportunities and challenges in an evolving market

Ortiz-Heredia, María A.¹; González-Lozano, Miguel²; Ortega-Cerrilla, María E.¹; Bárcena-Gama, José R.¹; Rogers-Montoya, Nathaniel A.³; Domínguez-Olvera, Daniel A.^{3*}

¹ Posgrado en Recursos Genéticos y Productividad-Ganadería. Colegio de Postgraduados, Campus Montecillo, Montecillo, Texcoco, Estado de México, México. C.P. 56264.

² Centro de Enseñanza, Investigación y Extensión en Producción Porcina, Facultad de Medicina Veterinaria y Zootecnia, Universidad Nacional Autónoma de México. Jilotepec, Estado de México. México. C.P. 54240.

³ Departamento de Genética y Bioestadística, Facultad de Medicina Veterinaria y Zootecnia, Universidad Nacional Autónoma de México. Ciudad Universitaria, Colonia C.U., Coyoacán, Ciudad de México, México. C.P. 04510.

* Correspondence: iazdalonso@gmail.com

ABSTRACT

Objective: This review article examines the economic benefits of animal welfare, focusing on how welfare-friendly practices can improve production efficiency and open new market opportunities.

Design/Methodology/Approach: The review draws on a critical analysis of existing literature on animal welfare and its economic impact, considering both the direct and indirect benefits of these practices.

Results: The findings show that animal welfare enhances product quality, lowers long-term costs, and offers competitive advantages in a market increasingly concerned with animal ethics. Effective management also helps prevent economic losses by maximizing the production system's potential.

Limitations of the Study/Implications: Although implementing animal welfare practices may require upfront investments in infrastructure and management, the long-term benefits include greater profitability and access to new markets. Distinguishing between direct and indirect benefits is therefore essential to maximizing economic returns.

Findings/Conclusions: Prioritizing animal welfare is not only a moral responsibility but also provides significant economic and social benefits. Embedding animal welfare into agricultural strategies can foster a more sustainable and prosperous future for all stakeholders.

Keywords: Animal welfare, livestock sustainability, profitability.

Citation: Ortiz-Heredia, M. A., González-Lozano, M., Ortega-Cerrilla, M. E., Bárcena-Gama, J. R., Rogers-Montoya, N. A., & Domínguez-Olvera, D. A. (2026). Economics of Animal Welfare: opportunities and challenges in an evolving market. *Agro Productividad*. <https://doi.org/10.32854/8p152f18>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: August 19, 2025.

Accepted: January 29, 2026.

Published on-line: April 16, 2026.

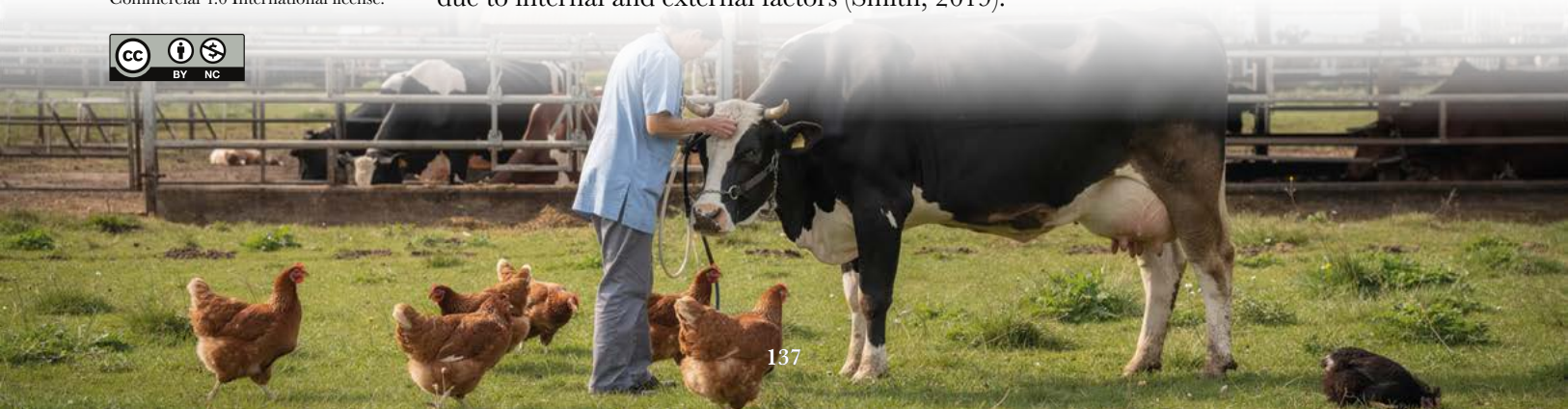
Agro Productividad, 19(2). February, 2026. pp: 137-150.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Animal welfare is the state in which an animal adapts to and copes with its physical and social environment, integrating its physical and mental condition across living and dying circumstances, thus enabling a quality-of-life assessment from the animal's perspective (Hernández & Martínez, 2020; García & López, 2018). This perspective recognizes that even under similar circumstances, individuals may experience different levels of well-being due to internal and external factors (Smith, 2019).



Stress, understood as the organism's adaptive response to environmental challenges, can aid adaptation and survival. However, when excessive or prolonged, it undermines animal welfare (Hernández & Martínez, 2020). The concept has since broadened into an integrated framework that also addresses social, economic, and sustainability dimensions, known as One Welfare (Mellor *et al.*, 2020). Animal welfare assessment was historically guided by the "Five Freedoms," though these have been found to sometimes conflict and offer limited measurability. Today, the "Five Domains" model is the preferred framework, providing an objective, science-based evaluation of nutrition, environment, health, behavior, and mental state (Mellor *et al.*, 2020; Mellor & Beausoleil, 2015). Economic factors are also significant, as animal welfare influences productivity and the market value of animal products, yet a purely utilitarian view is discouraged (Fraser, 2008).

Legally, some countries now recognize animals as sentient beings with rights, highlighting welfare as an intrinsic value rather than solely an economic consideration (Cicardini-Milla, 2022). Welfare is assessed using both direct indicators (physiological and behavioral) and environment-based measures, with a clear understanding of each species' normal behavior being essential (Whay *et al.*, 2003).

While ethical, legal, and scientific consensus is spreading around the welfare of food animals, adoption remains varied across livestock systems because the benefits of welfare improvements generally require upfront investments and recurrent management costs, whereas their economic returns are uncertain, shared by multiple actors and are conditioned by verification and governance devices. This generates a well-defined economic challenge in which producers and intermediaries must determine the if, when, and how of welfare investment under incomplete information, heterogeneous willingness-to-adopt and changing enforcement. In this context, it is important to be aware of the most relevant economic channels through which animal-friendly practices impact: (1) production-related results (health, losses and productivity; and product quality) and (2) indirect market outcomes (price premiums, market access, reputational risk, and regulatory compliance). This review hypothesizes that welfare investments are most likely to generate positive net returns when efficiency gains and market rewards together outweigh incremental costs. By integrating available evidence into a unified economic frame, the article addresses a gap in the animal welfare literature, which is often rich in ethical and biological arguments but less explicit about decision-relevant economic mechanisms and the conditions under which welfare becomes a competitive strategy in livestock systems.

MATERIAL AND METHODS

A narrative review was conducted, gathering literature about animal welfare and its economic consequences from the official sources and peer-reviewed articles. Provision of outputs was structured under a decision-focused framework that separates direct channels either enhancing animal health, loss avoidance, productivity or product quality from indirect ones (price premium, market access, reputational risk and regulatory compliance). It was organized in thematic sections reflecting mechanisms, from a conceptual foundation to economic outcomes.

Animal welfare as a key pillar of market dynamics

Evidence

Animal welfare is a fundamental concept, referring to the fulfillment of animals' basic needs, which must be met without exception. Understanding its economic relevance requires defining the market as the exchange of goods and services between different entities. As Herrera (2013) notes, market research aims to gather information that supports decision-making and guides long-term planning. In this context, it is essential to explore how animal welfare can address specific needs in different scenarios and how these opportunities may contribute to economic advantage.

The animal welfare market shows strong growth potential, driven by increasing public awareness of ethical animal treatment and rising demand for products that meet high welfare standards. This trend offers producers and marketers the opportunity to adapt their practices and products to align with consumer expectations, as animal welfare becomes a progressively more important factor in purchasing decisions (Cicardini-Milla, 2022). Moreover, implementing regulations that promote animal welfare can yield economic benefits for both producers and consumers by enhancing product quality and fostering sustainable practices (Broom, 2011).

In Mexico, animal welfare legislation exists but is poorly enforced. For instance, the Official Mexican Standard NOM-045-ZOO-1995 sets zoosanitary requirements for handling animals in markets, yet many operate in violation of these rules (FMVZ-UNAM, 2021). Inadequate infrastructure in such markets undermines animal welfare and poses a public health risk due to the sale of animals under unsuitable sanitary conditions.

Initiatives led by institutions such as SENASICA and UNAM have proven effective in improving market conditions. Training programs and the dissemination of animal welfare regulations have brought about significant changes in vendor behavior (FMVZ-UNAM, 2021). Nevertheless, sustained efforts are vital to consolidate these gains and prevent a relapse into harmful practices.

Economic implications

Overall, the evidence suggests that animal welfare operates as a market attribute that shapes consumer demand, competitive positioning, and regulatory compliance. As demand for welfare certified products increases, producers face a combination of incentives and constraints that ultimately determine profitability and investment orientation. These include potential price premiums and improved market access, as well as the costs of infrastructure upgrades, staff training, and ongoing monitoring. Poor welfare can generate negative externalities, including public health risks and reputational damage, particularly where enforcement is weak, and it can limit the market's ability to capture surplus from welfare improvements. Conversely, where education and regulation strengthen compliance, welfare enhancement can generate economic returns through premiums linked to higher perceived quality, lower losses associated with poor handling, and greater consumer trust when institutional efforts are sustained.

Legal framework of animal welfare: challenges and opportunities for implementation

Evidence

In many countries, animal welfare legislation aims to align with the guidelines of the World Organization for Animal Health (OIE) while also reflecting earlier regulations, codes of good practice, technological innovations, and scientific progress (Huertas *et al.*, 2014). Morales and Morales (2017) describe laws that still classify animals as “things” as “archaic and regressive.” In recent years, however, growing public concern for animal welfare has begun to challenge legal frameworks that reduce animals to mere property (Brels, 2012; Morales and Morales, 2017).

Although Mexico’s animal welfare regulations date back to 1940, Morales and Morales (2017) argue that public policies have fallen short of adequately protecting domestic species. In response, several states have enacted specific laws to prevent animal cruelty and ensure humane treatment. These regulations promote responsible ownership and impose administrative penalties for violations (Ambrosio-Morales, 2017).

The 2007 Federal Animal Health Law marked a milestone in Mexico’s animal welfare legislation by setting standards for the treatment of animals raised for livestock production. However, its implementation is hindered by the lack of effective enforcement mechanisms and adequate public policies (Morales & Morales, 2017). While regulations exist to ensure the humane treatment of animals for human consumption, they are frequently viewed as insufficient or unclear.

Effective enforcement of animal welfare standards is crucial. Current regulations impose stricter penalties, which can lead to financial losses for companies or imprisonment for offenders. However, the variation in state-level laws results in a confusing and fragmented enforcement landscape (Rivero-Sosa, 2017).

Economic implications

Producing and value chain actors face unambiguous economic incentives and risks in this legal environment. Higher penalties would in theory make the cost of non-compliance (expressed through fines, lawsuits or possible business interruptions) more costly while loose and poorly enforced rules reduce predictability required to be able to invest in welfare improvements. In these circumstances, the economic returns to welfare investment are influenced by not just on-farm costs but also regulatory predictability, level of enforcement, and capacity to convert compliance into market entry and reputational gains.

Consumer interest in animal welfare: a key driver of the sector’s economy

Evidence

Consumer interest in animal welfare has become a decisive factor in driving the adoption and continuation of practices that guarantee the ethical treatment of animals (Matas, 2013).

Consumers today can make informed choices about their food, selecting products such as free-range eggs or meat from humanely raised animals. However, the allowance of products with verified animal welfare standards remains limited (Lusk, 2011).

Studies indicate that consumers are willing to pay a premium for products that ensure animals are treated humanely and without cruelty (Matas, 2013; Huertas *et al.*, 2014; Moyano *et al.*, 2015). This willingness is driven both by inherent human empathy and by the belief that better animal welfare leads to higher-quality products (Moyano *et al.*, 2015).

Worldwide, demand for cruelty-free products is rising, fueled by international markets and regulations designed to uphold ethical production standards (Huertas *et al.*, 2014). In developed countries, consumers focus not only on price and food safety but also on production conditions, including the handling, transport, and slaughter of animals. In lower-income nations, meeting basic needs remains the priority; however, a growing segment of consumers is willing to pay a premium for products that guarantee humane animal treatment.

Economic implications

These trends suggest that animal welfare is becoming a marketplace attribute which could generate price premiums, build brand equity and open doors to regulated or premium market segments. Simultaneously, the small availability of substantiated welfare products indicates that there are supply side constraints (such as certification costs and monitoring, but also investment in welfare related infrastructure and management). With increased awareness, noncompliance will be economically relevant: not achieving welfare aspirations or benchmarks may lead to loss of consumer confidence and demand with follow-on revenue impact and reputational damage. Given such context, the profitability of welfare improvements relies on the trade-off between additional output and verification costs on the one hand and market returns -in terms of premiums offered or increased access to the market- and reduction in risk exposure within markets on the other.

Labeling and certification in the economics of animal welfare

Evidence

In developed nations, a well-established market for animal products has emerged, driven by consumer interest in animal welfare and the resulting adoption of stricter regulations.

In the Netherlands, initiatives have been introduced to establish high animal welfare standards, segmenting the market into three tiers: Conventional, meeting only the minimum legal requirements; Mid-Market, offering products that surpass conventional standards but fall short of organic; and Premium, encompassing organic products or those that meet the highest animal welfare criteria (Gocsik *et al.*, 2015).

Producers may determine their level of commitment to animal welfare, which entails complying with auditable standards and submitting to regular inspections. Some have gone further by installing surveillance cameras to support and streamline these processes (Lusk, 2011; Gocsik *et al.*, 2015).

In many countries, verification protocols are designed to be both accessible and flexible, encouraging producers to implement systems that promote animal welfare. However, once higher welfare standards are achieved, producers are expected to uphold them consistently. Despite progress, many countries offer no government incentives, and regulations are often seen as overly strict and rigid in enforcement. As a result, some producers resist adopting

animal welfare practices, particularly when added costs are not offset by higher sale prices. However, products meeting high animal welfare standards can command substantially different prices depending on certification level. Gocsik *et al.* (2015) note that the economic benefits linked to the highest welfare standards are significant.

Economic implications

This evidence suggests that animal welfare standards are promoting a differentiated market structure in which compliance and verification function as quality signals, enabling segmentation and price discrimination. These tiered systems allow producers to choose an adoption pathway that fits their cost structure and investment capacity. At the same time, audits and monitoring increase both fixed and variable costs related to certification, inspections, documentation, and, where relevant, surveillance technology. In the absence of public incentives, adopting welfare measures becomes a business decision. Uptake is more likely when price premiums, access to contracts, or reduced risk compensates for the added costs. Because certification premiums tend to rise with higher levels of compliance, the greatest potential rents lie at the top tiers, but realizing them depends on credible verification, sustained adherence to standards, and market conditions that translate welfare attributes into higher sale prices.

Infrastructure as a tool for animal welfare: economic implications

Evidence

Optimal facility design should ensure safety, functionality, and protection from environmental conditions (Grandin, 2008), while also minimizing social tension and stress (Lindberg, 2001). Space allowance refers to the area an individual needs to remain comfortable and free from social stress (Kido-Cruz *et al.*, 2022). Research shows that animal behavior and social hierarchy are highly influenced by housing conditions and space allowance (Kondo & Hurnik, 1990), which in turn impact many aspects of production and, ultimately, animal welfare (DeVries *et al.*, 2004; Landaeta-Hernández *et al.*, 2004).

Landaeta-Hernández and Drescher (2011) emphasize that facility design should prioritize animal welfare over purely economic considerations. For pig production, studies show that retrofitting existing facilities can cost 25% to 45% more than constructing them initially with suitable design and infrastructure.

Economic implications

Designing facilities that provide adequate space allowance not only enhances animal welfare but also delivers long-term economic gains. Landaeta-Hernández (2011) reports that providing animals with more space enhances their health and overall welfare, leading to higher productivity and improved product quality. For instance, Lee *et al.* (2012) compared steers housed at 8 m² and 32 m², finding that increased space boosted average daily gain (ADG) and rib eye area (REA). Animals in optimal conditions are less susceptible to stress and disease, lowering veterinary costs and minimizing losses from mortality or poor performance (Arrebola *et al.*, 2014). Thus, investing in well-designed facilities is both

an ethical commitment to animal welfare and a sound financial strategy that can improve profitability for producers.

Economics of animal transport: costs, benefits, and welfare opportunities

Evidence

Rising market demand has driven up production costs linked to animal transport, particularly for long-distance journeys. Inefficient transport can cause 26% to 76% losses, depending on the species, and is further exacerbated by poor ventilation and road accidents. Such accidents often stem from extended work hours, inadequate routes, and corporate pressure to meet demanding delivery targets (Miranda-de la Lama, 2013).

Implementing robust tools and protocols to reduce physiological stress during pre-slaughter handling and transport is critical. Pre-slaughter stress, often underestimated, has a substantial impact on animal welfare and on final product quality.

Quantifying transport costs is challenging, but effective management can cut them by up to 25% when key factors are addressed, such as: proper handling at origin, reasonable travel times, appropriate vehicles, trained staff, suitable loading densities, and optimal routes (Miranda-de la Lama, 2013). Accordingly, investing in transport improvements is crucial to ensure animal welfare and enhance sector profitability.

Pre-slaughter transport stress is a key driver affecting animal welfare and profitability in the meat sector. Recent evidence shows the resulting economic losses are measurable and multifaceted, degrading meat quality and reducing slaughterhouse efficiency.

DFD (dark, firm, dry) meat, caused by pre-slaughter glycogen depletion, can reduce carcass value by up to 30% (Miranda-de la Lama *et al.*, 2017). In cattle, average losses are about \$88.58 per carcass, with prevalence reaching 47.63% in some Mexican plants. Transport-related trauma also leads to condemnations costing roughly USD 146 per animal in South American systems, largely due to overloaded vehicles, slippery floors, and aggressive handling with electric prods (Temple *et al.*, 2016).

Transport mortality varies by region —0.03 to 0.5% in Europe for trips under 8 h— but under extreme conditions total losses can reach 20%. Additional losses arise from pre-slaughter liveweight loss due to dehydration (5-8% in heifers) and from bruising that reduces carcass yield. These risks intensify on long journeys (>12 h), where fasting and commingling unfamiliar groups heighten physiological stress (González-Rivas *et al.*, 2020). Miranda-de la Lama *et al.* (2017) present a logistics optimization model that can cut costs by 25% by:

- setting appropriate loading densities (0.7–1.7 m²/animal) to reduce slips and injuries.
- training staff in low-stress, non-aversive handling to limit the use of electric prods.
- upgrading vehicle design, with non-slip flooring and forced ventilation to stabilize in-vehicle temperature.

These measures maintain meat quality by keeping final pH within 5.4-5.8 and preserving water-holding capacity, thereby minimizing postmortem drip loss.

Economic implications

This evidence indicates that transport is both a welfare sensitive stage and a major cost center, where preventable stress and injury translate into measurable economic losses through reduced carcass value, condemnations, mortality, dehydration related shrink, bruising, and lower slaughterhouse efficiency. Because these losses tend to be concentrated in long distance journeys and are amplified by operational factors such as routing, loading density, vehicle condition, and handling practices, targeted improvements in transport management can generate high returns. In particular, measures that reduce stress and trauma are likely to pay off through lower losses and more consistent meat quality, while logistics optimization and staff training can reduce costs and strengthen compliance with welfare expectations, improving profitability across the value chain.

Animal welfare and product quality: a sustainable economic relationship

Evidence

Animal stress markedly degrades meat quality, altering physical and sensory attributes. Stress-driven hormonal shifts; especially around handling and pre-slaughter, can result in PSE (pale, soft, exudative) or DFD meat, depending on species and circumstances (Rodríguez-Calleja *et al.*, 2005; Barbut *et al.*, 2008).

These effects impair meat appearance, shorten shelf life, and increase susceptibility to bacterial contamination (Eikelenboom *et al.*, 1990).

DFD meat has lower market value because consumers link its color to poor quality. On the other hand, PSE meat often shows off-odors and higher cook loss, leading to substantial economic losses (O'Neill *et al.*, 2003). Thus, effective pre-slaughter stress management is essential to ensure meat quality.

Injuries incurred during loading, transport, and unloading can seriously compromise meat quality. Common injuries, such as bruises, fractures, and muscle tear, stem from the physical and psychological stress animals undergo at these stages (Pérez *et al.*, 1999).

Bruises (hematomas) are blood accumulations from ruptured capillaries that make meat unfit for consumption and subject to condemnation (Paramio, 2000). Wounds also promote bacterial growth and hasten spoilage (Arrebola *et al.*, 2014). Evidence shows that poor transport conditions markedly raise bruising-related condemnations, degrading product quality and driving substantial economic losses for producers (Godoy *et al.*, 1986; Eikelenboom *et al.*, 1990).

Hides are valuable by-products, but they are easily damaged by poor handling along the chain, both pre- and post-slaughter (Acero, 2009). Improving transport welfare and adopting proper handling practices increases hide value and reduces losses; mistreatment degrades not only hides but also the overall quality of meat products (Acero, 2009; Arrebola *et al.*, 2014).

Stress and mishandling can cause bruising and tissue damage, lowering market value and driving substantial losses for producers (Godoy *et al.*, 1986; Eikelenboom *et al.*, 1990). Prioritizing animal welfare is therefore essential; not only on ethical grounds, but because it improves product quality and profitability.

Animal mistreatment directly undermines the quality of animal-derived products. Prioritizing profit over welfare harms animal health and, in turn, reduces the quality of meat and by-products. The consequences are both ethical and economic: low-quality outputs translate into substantial losses for the industry (Télliez, 2022; CIWF, 2021).

Economic implications

Taken together, these data show that stress and mishandling generate financial losses at multiple points in the chain through reinforcing pathways. These include carcass downgrading, such as PSE or DFD, shorter shelf life and higher contamination risk, condemnations due to bruising and wounds, and the loss of value in co-products such as hides. Because these losses occur at identifiable stages, including the farm, transport, and handling, welfare-oriented management functions as a practical quality assurance tool that protects revenue and reduces waste. Accordingly, investments in low-stress handling, improved transport conditions, and effective preslaughter stress control can increase profitability by preserving product quality, raising the share of saleable output, and maintaining the value of by-products.

How welfare practices affect income

Evidence

Poor animal welfare leads to production losses such as: lower performance, reduced by-product quality, animal injury and mortality, and inefficient resource use; and can even constitute a criminal offense.

Economic implications

Consequently, investing in animal welfare can generate revenue through multiple channels. Adopting robust welfare practices can reduce avoidable losses and improve productivity; low-stress handling enhances by-product quality and overall system efficiency, translating into greater revenue (Acero, 2009; Arrebola *et al.*, 2014). Humane, ethical handling also helps secure production by safeguarding quality and reducing the risk of condemnation and other losses that directly impact revenue, while consistent quality can strengthen consumer loyalty and producer reputation (Télliez, 2022). In addition, prioritizing animal welfare can expand access to new markets by attracting buyers who value ethically produced goods, enabling premium pricing and strengthening competitiveness in domestic and export contexts (FAO, 2023). Overall, animal welfare is both an ethical imperative and a sound economic strategy, as welfare-focused practices can enhance profitability and support the long-term sustainability of livestock operations.

Animal welfare: a strategy for sustainable production

Evidence

Animal welfare is a pillar of modern livestock production, with benefits that extend well beyond regulatory compliance. In many countries, legal recognition and protection of animals are expanding, reinforcing the state's duty to safeguard animal rights for future generations (Rivero-Sosa, 2017).

Globally, animal-protection movements have driven the adoption of welfare standards and regulations. Beyond the ethical case, these advances open access to domestic and international markets for producers.

The rising concern of consumers for ethical animal treatment shapes their purchasing decisions and enhances producers' reputations (Infortambo Andina, 2022). Animal welfare also delivers economic gains: adopting good practices improves efficiency and product quality. Proper handling during transport and slaughter elevates meat and by-product quality, strengthening market competitiveness (OMSA, 2024).

Economic implications

Investing in animal welfare is therefore both an ethical imperative and a sound economic strategy that benefits animals and producers alike. Aside from the ethical argument, such developments can provide producers with access to national and international markets. Key advantages include lower disease pressure due to reduced illness and less veterinary intervention, increased product quality through improved handling, better market access via improved sentinel measures compared with current standards and more consumer confidence as welfare enters more buying decisions. And in general, increasing the productive potential of any production system either raises productivity or leads to economic gains. Animal welfare is a moral and financial imperative. If we invest in animal welfare.

Economic balance: direct and indirect production benefits

At first glance, animal welfare may not appear to yield direct profits, yet it is crucial for production efficiency and market access (see Table 1). As Forbuena-Borrás (2017) notes, it helps to distinguish between direct and indirect gains. The direct gains include cost reductions in the final product, since good handling prevents defective inputs, shortens processing, and, by speeding time to market, lowers mortality and morbidity, boosting profitability.

Indirect gains stem from better product quality: humane handling produces more uniform, higher-quality products. This adds value to processed goods: products from well-treated animals are typically of higher quality than those from stressed or mistreated animals (Forbuena-Borrás, 2017). Research also supports these findings; for example,

Table 1. Economic Impact of Improving Animal Welfare on Productivity.

Aspect	Economic impact	Reference
Meat product quality.	10-20% improvement and fewer defects.	OMSA (2024)
Disease burden.	15-30% lower veterinary costs with better management.	Huertas <i>et al.</i> (2021)
Productivity.	Up to 25% more piglets per sow per year under improved welfare.	Jääskeläinen <i>et al.</i> (2014)
Worker safety.	Savings up to \$5,000 per facility/year from fewer injuries.	OMSA (2024)
Reproductive performance.	10-15% shorter inter-farrowing interval with good practices.	Jääskeläinen <i>et al.</i> (2014)
Premium markets.	15-30% higher prices for certified, welfare-standard products.	Agrovet Blog (2023)
Feed efficiency.	Up to 20% less feed per animal due to better health and lower stress.	OMSA (2024)
Social & environmental outcomes.	5-10% higher social acceptance and improved system sustainability.	OMSA (2024)

Romo-Valdez *et al.* (2021) found that cattle provided with an appropriate environment and adequate space allowance achieve superior growth and performance, reducing operating costs and boosting productivity.

Enhancing logistics and transport conditions can cut operating costs by up to 25% (Miranda-de la Lama *et al.*, 2019). Preventive health programs further reduce veterinary spending by 30-40% (Sánchez Rodríguez Castillo, 2023).

Animal welfare reduces stress and disease, lowering veterinary costs and boosting production efficiency. From a market standpoint, meeting welfare standards strengthens public trust and opens access to domestic and international markets.

Rising demand for ethical, sustainable goods is leading consumers to favor products that ensure humane animal treatment (OMSA, 2024).

CONCLUSIONS

This review is distinctive in that it integrates ethical considerations and welfare outcomes within an explicit economic theory framework. It clarifies the mechanisms through which welfare interventions affect performance by separating direct production impacts, such as productivity gains and loss reduction, from indirect market and governance effects, such as reputational risk, market access, and regulatory compliance. Welfare investment becomes economically efficient when verification is credible and enforcement is predictable, allowing compliance to translate into measurable financial returns. Under these conditions, animal welfare programs are not only ethically justified but also economically compelling, improving operational efficiency, product quality, and consumer trust, and thereby strengthening competitive positioning. Strategically targeted investments in infrastructure and transport can further reduce avoidable losses, lower costs, and raise rates of return. As demand for humane practices continues to grow, producers that adopt these measures are better positioned to contribute to public welfare and to remain viable in an increasingly competitive marketplace, with animal welfare becoming a core element of long-term agricultural strategy.

REFERENCES

- Acero Adámed, P. (2009). Planificación y manejo de la explotación de vacuno de carne (Tomo II). Colección Prácticas Agropecuarias. Consejería de agricultura y ganadería. https://d1wqtxts1xzle7.cloudfront.net/34385273/VACUNO_CARNEop-libre.pdf
- Alende, M. (2011). Bienestar animal y reducción del estrés en el feedlot. Estación Experimental Agropecuaria Anguil, La Pampa. https://www.produccion-animal.com.ar/informacion_tecnica/invernada_o_engorde_a_corral_o_feedlot/96-Bienestar.pdf
- Ambrosio Morales, M. T. (2017). El maltrato y la crueldad contra los animales: Su importancia desde la perspectiva de la criminología. En M. T. Ambrosio Morales & M. Anglés Hernández (Eds.), *La protección jurídica de los animales* (pp. faltantes). Instituto de Investigaciones Jurídicas, Universidad Nacional Autónoma de México.
- Arrebola Molina, F. A., Elías Ordoñez, M., & Yruela Morillo, M. (2014). Bienestar animal en explotaciones porcinas. Junta de Andalucía. Consejería de Agricultura, Pesca y Desarrollo Rural. <https://www.juntadeandalucia.es/servicios/publicaciones/detalle/77764.html>
- Arrebola, M. (2014). Impact of transport stress on meat quality. *Meat Science*. <https://doi.org/10.1016/j.meatsci.2014.03.002>
- Barbut, S., Sosnicki, A. A., Lonergan, S. M., Knapp, T., Ciobanu, D. C., Gatcliffe, L., & Wilson, E. W. (2008). Progress in reducing the pale, soft and exudative (PSE) problem in pork and poultry meat. *Meat Science*, 79(1), 46-63. <https://doi.org/10.1016/j.meatsci.2007.07.031>

- Bennett, R. (1998). Investigando los estilos musicales. Akal.
- Brels, S. (2012). Tendencias actuales en bienestar animal. *Revista de Protección Animal*, 5(1), 23-30.
- Brels, S. (2012). La protección del bienestar animal: Una preocupación universal que se debe considerar globalmente y seriamente en derecho internacional. *Derecho Animal. Forum of Animal Law Studies*, 3(2), 1-6. <https://doi.org/10.5565/rev/da.178>
- Broom, D. M. (2011). Animal welfare: An old and new concept. *Journal of Animal Science*, 89(3), 1-10.
- Broom, D. M. (2011). Bienestar animal: Conceptos, métodos de estudio e indicadores. *Revista Colombiana de Ciencias Pecuarias*, 24(3), 306-321. <https://www.redalyc.org/pdf/2950/295022382010.pdf>
- Cicardini Milla, D. (2022). Proyecto de ley “que modifica el código civil en relación a la categoría de cosas corporales muebles de los animales y los reconoce como seres sintientes” (Boletín 14993-12). Cámara de Diputadas y Diputados de Chile.
- Cicardini Milla, J. A. (2022). Bienestar animal y su impacto en la producción agrícola. *Revista Mexicana de Ciencias Pecuarias*, 13(1), 45-58.
- Compassion in World Farming (CIWF). (2021). Crueldad animal. Recuperado el 29 de enero de 2025, de <https://www.ciwf.es/campaigns/crueldad-animal/>
- DeVries, T., von Keyserlingk, M., & Weary, D. (2004). Effect of feeding space on the inter-cow distance, aggression, and feeding behavior of free-stall housed lactating dairy cows. *Journal of Dairy Science*, 87, 1432-1438. 10.3168/jds.S0022-0302(04)73293-2
- DeVries, T. J. (2004). The influence of space allowance on the behavior and welfare of cattle. *Applied Animal Behaviour Science*, 88(3-4), 277-290.
- Eikelenboom, G., Bolink, A. H., & Sybesma, W. (1991). Effects of feed withdrawal before delivery on pork quality and carcass yield. *Meat Science*, 29(1), 25-30. [https://doi.org/10.1016/0309-1740\(91\)90020-Q](https://doi.org/10.1016/0309-1740(91)90020-Q)
- Food and Agriculture Organization of the United Nations (FAO). (2023). Bienestar animal: Un enfoque para mejorar la producción sostenible. Recuperado el 29 de enero de 2025, de <https://www.fao.org/welfare-animal/en/>
- Facultad de Medicina Veterinaria y Zootecnia, Universidad Nacional Autónoma de México (FMVZ-UNAM). (2021). Participación de la Facultad de Medicina Veterinaria y Zootecnia en el bienestar animal. https://fmvz.unam.mx/fmvz/principal/archivos/Bienestar_animal_mercados_ganaderos.pdf
- Fombuena Borrás, V. (2017). Descripción de ventajas económicas directas e indirectas en la aplicación de ensayos no destructivos (END) en un proceso productivo. <http://hdl.handle.net/10251/82149>
- Forbuena Borrás, V. (2017). Ventajas económicas del bienestar animal. Recuperado de <https://www.agrovetmarket.com/beneficios-economicos-bienestar-animal>.
- Francés, M. J. P. (2010). La importancia de enseñar economía. *Pedagogía Magna*, (8), 134-138. <https://dialnet.unirioja.es/descarga/articulo/3628034.pdf>
- Gocsik, E., Henningsen, A., & Matzdorf, B. (2015). The impact of animal welfare on market outcomes: Evidence from the Netherlands. *Journal of Agricultural Economics*, 66(1), 1-20.
- Gocsik, É., Oude Lansink, A. G. J. M., Voermans, G., & Saatkamp, H. W. (2015). Economic feasibility of animal welfare improvements in Dutch intensive livestock production: A comparison between broiler, laying hen, and fattening pig sectors. *Livestock Science*, 182, 38-53.
- Godoy, M. (1986). Effects of transport duration on bruising in cattle. *Veterinary Record*. <https://doi.org/10.1136/vr.119.12.277> (Consultado el 29 de enero de 2025)
- González-Rivas, P. A. (2020). Effects of heat stress on animal physiology, metabolism, and meat quality: A review. *Meat Science*, 162, 108025. <https://doi.org/10.1016/j.meatsci.2019.108025>
- Grandin, T., & Deesing, M. (1998). Genetics and behavior during handling, restraint and herding. En T. Grandin (Ed.), *Genetics and the behavior of domestic animals* (pp. 113-144). Academic Press.
- Grandin, T. (2008). Improving animal welfare in beef slaughter plants: A review of the literature. *Journal of Animal Science*, 86(E-Suppl), E1-E11.
- Herrera, J. E. P. (2013). Investigación de mercado: Un enfoque práctico. *Revista Internacional de Marketing*, 5(2), 15-28.
- Herrera, J. E. P. (2013). ¿Cómo se hace una investigación de mercados?. En J. E. P. Herrera (Ed.), [investigación de mercados] (cap. 3, pp. 133-150). Ecoe Ediciones.
- Huertas, J., García, M., & López, R. (2014). Desarrollo y avance en la legislación sobre bienestar animal. *Revista Mexicana de Ciencias Veterinarias*, 12(3), 45-60.
- Huertas, S. M., Gallo, C., & Galindo, F. (2014). Motores de las políticas de bienestar animal en las Américas. *Revue Scientifique et Technique (Office International des Épizooties)*, 33(1), 55-66.
- Huertas, S., González, A., & Rodríguez, M. (2021). La importancia del bienestar animal en los sistemas de producción silvopastoriles y forestales. *Revista Ciencia Animal*, 12(2), 101-110.

- Infortambo Andina. (2022). Beneficios del bienestar animal. Recuperado de <https://infortamboandina.co/es/noticias/beneficios-del-bienestar-animal>
- Jääskeläinen, T., Kauppinen, T., Vesala, K.M., & Valros, A. (2014). Relationships between pig welfare, productivity and farmer disposition. *Animal Welfare*, 23(4), 435-443. <https://doi.org/10.7120/09627286.23.4.435>
- Kido-Cruz, M. T., Martínez-Castro, C. J., Zúñiga-Marroquín, T., & Cotera-Rivera, J. (2022). Estimación del bienestar animal del bovino lechero en trópico, mediante criterios de acondicionamiento ambiental. *Revista MVZ Córdoba*, 27(3), e2676. <https://doi.org/10.21897/rmvz.2676>
- Kondo, S., & Hurnik, J. F. (1990). Stabilization of social hierarchy in dairy cows. *Applied Animal Behaviour Science*, 27, 287-297. [https://doi.org/10.1016/0168-1591\(90\)90125-W](https://doi.org/10.1016/0168-1591(90)90125-W)
- Kondo, S., & Hurnik, J. F. (1990). Effects of space allowance on the behavior of pigs in a group housing system. *Applied Animal Behaviour Science*, 27(1), 51-62.
- Landaeta Hernández, A. J. (2012). Instalaciones, conducta y bienestar animal en vacunos tropicales. *Mundo Pecuario*, 8(2), 121-131. https://www.produccion-animal.com.ar/etologia_y_bienestar/bienestar_en_bovinos/61-instalaciones.pdf
- Landaeta-Hernández, A. J., & Drescher, M. (2011). Espacio vital en sistemas de producción animal: Implicaciones para el bienestar animal. *Revista Brasileira de Zootecnia*, 40(3), 561-568.
- Lee, C., Hales, K. E., & Shike, D. W. (2012). Effects of increased space allocation on performance and behavior of feedlot steers. *Journal of Animal Science*, 90(Suppl. 3), 506-507
- León Guzmán, M. (2006). El bienestar animal en las legislaciones de América Latina. *Ciencias Veterinarias*, 24(2), 185-221. <https://www.revistas.una.ac.cr/index.php/veterinaria/article/view/4784>
- Lusk, J. L. (2011). Consumer preferences for animal welfare: A review of the literature. *Agricultural and Resource Economics Review*, 40(1), 1-19.
- Lusk, J. L. (2011). Consumer preferences for animal welfare: A review of the literature. *Agricultural and Resource Economics Review*, 40(1), 1-19.
- María, G. A., Villarroel, M., Sañudo, C., Olleta, J. L., & Gebresenbet, G. (2003). Effect of transport time and ageing on aspects of beef quality. *Meat Science*, 65(4), 1335-1340. [https://doi.org/10.1016/S0309-1740\(03\)00054-8](https://doi.org/10.1016/S0309-1740(03)00054-8)
- Matas Obrequé, C. (2013). Segmentación de consumidores según su actitud frente al bienestar animal en Santiago y Viña del Mar. <https://repositorio.uchile.cl/handle/2250/131635>
- Matas, A. (2013). El impacto del bienestar animal en las decisiones del consumidor. *Revista de Estudios Sociales*, 45(2), 25-34.
- McInerney, J. P. (2004). Animal welfare, economics and policy: Report on a study undertaken for the Farm and Animal Health Economics Division of Defra. UK Department for Environment, Food and Rural Affairs (Defra). <https://webarchive.nationalarchives.gov.uk/ukgwa/20130123162956/http://archive.defra.gov.uk/evidence/economics/foodfarm/reports/documents/animalwelfare.pdf>
- Miranda-de la Lama, G. C. (2013). Transporte y logística pre-sacrificio. SciELO México. Recuperado de https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0301-50922013000100004
- Miranda-de la Lama, G. C. (2019). Pre-slaughter cattle welfare indicators for use in commercial abattoirs. *Animals*, 9(6), 383. <https://doi.org/10.3390/ani9060383>
- Miranda-de la Lama, G. C., Villarroel, M., María, G. A. (2017). Behavioural and physiological profiles following transport in cattle: A multivariate analysis. *Applied Animal Behaviour Science*, 189, 22-29. <https://doi.org/10.1016/j.applanim.2017.01.003>
- Miranda de la Lama, G. C. (2013). Transporte y logística presacrificio: Principios y tendencias en bienestar animal y su relación con la calidad de la carne. *Veterinaria México*, 44(1), 31-56.
- Morales García, A. D., Morales García, J. J. (2017a). Reformas a la legislación ambiental asociado al bienestar animal en México. *dA. Derecho Animal: Forum of Animal Law Studies*, 8(2), 10-21. <https://www.raco.cat/index.php/da/article/view/v8-n2-morales>
- Morales García, A. D., & Morales García, J. J. (2017b). Bienestar animal y legislación: El reto de los animales destinados al consumo humano en México. *dA. Derecho Animal: Forum of Animal Law Studies*, 8(3), 1-24. <https://raco.cat/index.php/da/article/view/349379>
- Morales, J., & Morales, A. (2017). La cosificación del animal en la legislación mexicana. *Revista Jurídica Mexicana*, 15(2), 78-89.
- Moyano Estrada, E., Castro, F., & Prieto Gómez, J. (2015). Bases sociales y políticas del bienestar animal en la Unión Europea. <http://hdl.handle.net/10261/155377>
- Moyano, R., Salinas, M., & González, J. (2015). Percepción del bienestar animal: Implicaciones para el consumo responsable. *Revista Internacional de Sociología*, 73(1), 23-45.
- O'Neill, D. J., Lynch, P. B., Troy, D. J., Buckley, D. J., & Kerry, J. P. (2003). Effects of PSE on the quality of cooked hams. *Meat Science*, 64(2), 113-118. [https://doi.org/10.1016/S0309-1740\(02\)00117-1](https://doi.org/10.1016/S0309-1740(02)00117-1)

- Organización Mundial de Sanidad Animal [OMSA]. (2024). Bienestar animal: un bien vital para un mundo más sostenible. Recuperado de <https://www.woah.org/app/uploads/2024/01/es-omsa-visionpaper-bienestaranimal.pdf>
- Paramio, T. (2000). Manejo y producción de porcino: Breve manual de aproximación a la empresa porcina para estudiantes de veterinaria. Universitat Autònoma de Barcelona, Facultat de Veterinària. <http://bvirtual.infoagro.hn/xmlui/bitstream/handle/123456789/865/manual%20porcino%20final.pdf?sequence=1>
- Pordomingo, A. J. (2005). Feedlot: Alimentación, diseño y manejo (No. 636.2085). Instituto Nacional de Tecnología Agropecuaria.
- Rivero Sosa, I. G. (2017). Enfoque ético y jurídico de la protección animal. En M. T. Ambrosio Morales & M. Anglés Hernández (Eds.), *La protección jurídica de los animales*. Instituto de Investigaciones Jurídicas, Universidad Nacional Autónoma de México.
- Rivero-Sosa, M. (2017). Desafíos en la aplicación del bienestar animal en México. *Revista de Derecho Animal*, 10(1), 12-25.
- Rivero-Sosa, M. (2017). La protección jurídica de los animales: Un análisis contemporáneo. Recuperado de https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0187-55092017000100003
- Rodríguez Castillo, M. F. (2023). Bienestar en la producción de ganado bovino de carne*. Repositorio UAAAN. http://repositorio.uaaan.mx:8080/xmlui/bitstream/handle/123456789/49417/MAR%C3%8DA%20FERNANDA%20RODR%C3%8DGUEZ%20CASTILLO_locked.pdf
- Rodríguez Calleja, J. M., García López, M. L., Santos, J. A., & Otero, A. (2005). Development of the aerobic spoilage flora of chilled rabbit meat. *Meat Science*, 70(2), 389-394.
- Romo-Valdez, A. (2021). Impacto del bienestar animal en la producción bovina. Recuperado de <https://www.ganaderia.com/destacado/Bienestar-animal-del-ganado-vacuno>
- Téllez, M. (2022). La explotación animal y sus implicaciones éticas. *Revista de Ética Animal*. <https://www.revistaeticaanimal.com/articulo/explotacion-animal-implicaciones-eticas> (Consultado el 29 de enero de 2025)
- Temple, D., Mainau, E., & Manteca, X. (2016). Welfare issues during transport of pigs to slaughter. *Porcine Health Management*, 2(1), 1-8. <https://doi.org/10.1186/s40813-016-0035-0>

Productive dynamics and sugarcane supply management in a competitive environment: a study of three sugar mills in Jalisco

Macías-García, Edith R.¹; Santoyo-Cortés, Vinicio H.^{1*}; García-Chávez, Luis R.²
 Altamirano-Cárdenas, J. R.¹; González-Ramírez, María G.¹

¹ Universidad Autónoma Chapingo, Centro de Investigaciones Económicas, Sociales y Tecnológicas de la Agroindustria y la Agricultura Mundial (CIESTAAM), carretera federal México-Texcoco km 38.5, Texcoco, Estado de México, México. C. P. 56230.

² Universidad Autónoma Chapingo, Centro Regional Universitario de Occidente (CRUOC), Guadalajara, Jalisco, México. C. P. 45659.

* Correspondence: hsantoyo@ciestaam.edu.mx

ABSTRACT

Objective. To identify the profile of producers and analyze sugarcane supply strategies in a zone shared by three sugar mills in Jalisco, to propose lines of intervention that strengthen the sustainability of supply in a competitive environment.

Design/Methodology/Approach. Surveys, interviews, and statistical records were analyzed to develop a typology of growers based on the dynamics of cultivated land and to characterize the acquisition and retention strategies of sugar mills. The Delphi and MICMAC methods were used to explore different scenarios and support the analysis. Differentiated strategic actions derived from the analysis are proposed.

Results. Four producer profiles were identified: social, stable, diversifying, and specialized. Sugar mills implement differentiated strategies; one is focused on general supplier retention, another prioritizes large-scale growers, and a third operates based on close service to the suppliers as a value proposition. Prospective scenarios agree that sustainable production intensification is the main strategic approach in the face of reduced sugarcane cultivation area, and competition from alternative crops. Within this framework, diversifying and specialized sugarcane growers show greater potential to enhance sectoral productivity due to their openness to innovation and positive response to incentives.

Limitations/implications of the study. The study was based on a convenience sample of 42 producers, which limits the possibility of extrapolating the results to the entire production base. Likewise, the low participation of industry representatives and restrictions on the disclosure of information limit the possibility of comparing supply strategies in depth. However, the findings offer valuable information for other regions facing similar sugarcane supply challenges.

Findings/Conclusions. Current strategies lack effective targeting, preventing them from focusing on the actual capabilities of the production base. A shift towards differentiated supplier targeting and retention models is proposed, based on intensification, the building of organizational and technical capacities, and on establishing lasting links with agribusinesses.

Keywords: typology of producers, supplier retention, production restructuring, sugarcane supply.

Citation: Macías-García, E. R., Santoyo-Cortés, V. H., García-Chávez, L. R., Altamirano-Cárdenas, J. R., & González-Ramírez, M. G. (2026). Productive dynamics and sugarcane supply management in a competitive environment: a study of three sugar mills in Jalisco. *Agro Productividad*. <https://doi.org/10.32854/21fq1863>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: August 23, 2025.

Accepted: January 12, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 151-162.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Sugarcane is one of the most important crops in Mexico, both for social impact and economic value. The sugar agro-industry generates 500 000 direct jobs and 2.4 million indirect jobs, involving producers, farm laborers, cane cutters, transporters, and mill workers in more than 269 municipalities across the country (Gómez-Merino *et al.*, 2021). Jalisco is the second-largest Mexican sugarcane-producing state and faces a changing agricultural landscape due to the shift towards more profitable crops such as berries, avocados, agave, and vegetables according to the Mexican Committee for the sustainable management of sugarcane (Comité Nacional para el Desarrollo Sustentable de la Caña de Azúcar-CONADESUCA, 2024) y el Gobierno del estado de Jalisco (2023).

In the sugarcane harvests between 2014-2024 it was noticed that the area dedicated to agave grew by 107%, while the area of sugarcane decreased by 3.53% according to CONADESUCA (2024) and Mexico's Agri-Food and Fisheries Information Service (Servicio de Información Agroalimentaria y Pesquera-SIAP, 2024). This shift has caused increasing pressure on the supply system for sugar mills, especially in regions where multiple agribusinesses compete for a shared production base. Changes in production dynamics have impacted traditional governance processes. Agricultural producers value now not only prices, but also efficiency in logistics and institutional proximity (Susilowati *et al.*, 2020; Ghezzi *et al.*, 2022).

Strategic decision-making in the region is limited by the lack of effective targeting of the base of sugarcane growers, the lag in technological adoption, the aging of growers, the lack of sugarcane varieties renewal, and a sugarcane registry that does not distinguish active producers. Furthermore, the fragmentation of land ownership and the pursuit of social benefits limit the accurate identification of the sugarcane supply system (FAO & BID, 2007; CONADESUCA, 2024). This prevents supplier recruitment and retention strategies to be adapted to the capabilities, motivations, or levels of technological use of the different profiles of producers.

Within this context, the objective of this study was to identify the profile of producers and analyze sugarcane supply strategies in a zone shared by three sugar mills in Jalisco, to propose lines of intervention that strengthen the sustainability of supply in a competitive environment.

MATERIALS AND METHODS

This research was conducted in Valles y Lagunas de Jalisco, a zone shared by the sugar mills of Tala, Ameca, and Bellavista. A mixed-methods approach both exploratory and explanatory was used. To characterize the profile of producers, a semi-structured survey was administered to 42 sugarcane growers selected through non-probability convenience sampling, taking advantage of the meeting and payment points common to producers in municipalities such as Ameca, Tala, Magdalena, Etzatlan, and Ahualulco de Mercado, Jalisco (México).

The instrument was structured in four sections: producer identification, size and management of the production unit, family structure, and access to technical assistance and financing. Both open-ended and closed-ended questions were designed, allowing for

the collection of qualitative and quantitative data that included variables such as current and previous sugarcane cultivation area, water regime, technical assistance, level of technology, age, motivations, and links with sugar mills. For the construction of profiles, the current cultivation area and the area dedicated to cultivation 10 years ago were selected as key variables. Then, data were analyzed using scatter plots in order to classifying four groups: social growers, stable growers, diversifying growers, and specialized growers. Each group was defined with a threshold of up to 3 hectares for both variables to ensure statistical consistency. Data were stored and categorized in Excel® and were processed using descriptive statistics. This segmentation was compared with the Producers Registry of CONADESUCA (2024) to identify discrepancies with the official data on production and administrative structure.

In a second stage, interviews were conducted with technical and management staff from sugar mills, as well as with representatives of sugarcane grower organizations, addressing aspects such as the perception of problems, recruitment efforts, incentives, technical monitoring, technology use, and links with growers. As a complement to the main analysis, a prospective analysis based on the Delphi method was implemented by consulting a panel of eight experts selected by convenience sampling, based on their knowledge and experience in decision-making within the sugarcane production system (Cabrera Palafox, 2022). The agreed-upon statements were analyzed using the Cross-Impact Matrix and Multiplication Applied to a Classification (MICMAC) methodology, which allowed for the visualization of influence and dependence relationships among variables (Godet, 2000; Arango & Cuevas, 2012).

With the results, three prospective scenarios were constructed: sustainable consolidation, competition and adaptation, and sugarcane recovery in the face of the crisis with agave increasing production. Finally, the production profiles were cross-referenced with some of the strategic factors found in the scenarios, to propose segmented and differentiated lines of intervention, based on the experiences observed both in the field and in specialized literature, in order to prioritize criteria of technical feasibility and operational capacity.

RESULTS AND DISCUSSION

Our main results are described based on the prospective scenarios created, and discussion is structured around the elements identified as strategic for strengthening the sustainability of the sugarcane supply system, in a competitive environment challenged by production restructuring in the production systems.

Typology of producers

The pressure exerted by seemingly more profitable alternative crops has led to heterogeneous behavior among sugarcane growers. To understand this, a typology was constructed based on the variation in sugarcane cultivation area between 2014 and 2024 (Figure 1).

This segmentation allowed the identification of differentiated profiles of producers in terms of their motivations and the scale on which those influence their relationships with agribusinesses, and their participation in the regional sugarcane production system. Four

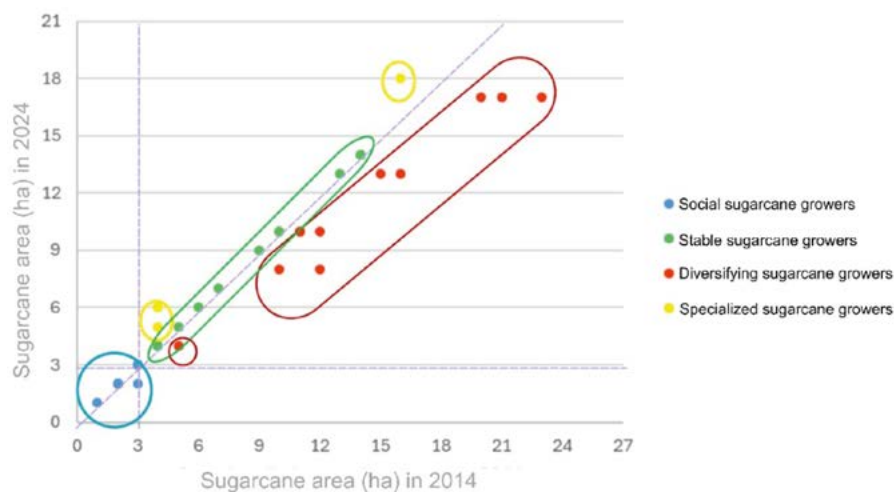


Figure 1. Producer profiles according to the behavior of the recent area dedicated to sugarcane cultivation (2024) compared to what was recorded as sugarcane cultivation in 2014.

profiles were distinguished. Social sugarcane growers: farmers with less than 3-hectares cultivation areas who have maintained these areas constant, prioritizing the social benefits associated with Mexico's National Registry of sugarcane growers —such as medical care provided by the government, pensions and subsidies—, over production profitability. They mostly come from families who continue the traditional sugarcane production, with low levels of technology, recording the lowest yields. Stable sugarcane growers: they grow sugarcane in medium-sized cultivation areas with no variation over the period evaluated. They are characterized by minimal technological adoption, risk aversion, and high dependence on third parties for agricultural labors. Their main motivation is the certainty of annual income derived from contracts with sugar mills.

The other two profiles described are Diversifying sugarcane growers: they are farmers that have reduced their sugarcane cultivation area to incorporate other crops, mainly agave. They are responsive to economic incentives, growing sugarcane as a backup crop. These growers maintain higher yields than the previous groups and are open to adopting new technologies. Finally, Specialized sugarcane growers: these large-scale farmers have increased their sugarcane cultivation areas in recent years. They are focused on improving yields, demonstrating greater investment capacity in cultivation and innovative agricultural practices. In addition, they are often influenced by younger generations and adhere to a more business-oriented approach in their operational models.

These differences influence how each producer profile relates to agribusinesses, also the types of incentives that are attractive for their recruitment and retention as suppliers by the sugar mills (Table 1).

Differentiated strategies of the sugar mills

Understanding how these profiles are configured allows us to assess the challenges that agribusinesses face in their relationships with the production base; also, the strategies implemented by each sugar mill to address these challenges. The sugar mills in the supply

Table 1. Producer profiles and their strategic links in the sugarcane supply system of the evaluated sugar mills.

Producer profile	Main motivation	Priorities of the producer	Tendency toward loyalty to a sugar mill
Social sugarcane growers	Social benefits	Stability and access to health services	High
Stable sugarcane growers	Financial stability and secure annual income	Timely payments and economic security	Medium (depending on payment punctuality and transparency)
Diversifying sugarcane growers	Maximization of household income through moderate diversification	Profitability	Low (they prefer productive and commercial flexibility)
Specialized sugarcane growers	Increase in future profitability through specialization	Long-term competitiveness and profitability	Low (younger producers constantly seeking better conditions)

zone evaluated have adopted different strategies in response to the competitive pressure generated by alternative crops. Although they operate in the same territory and under similar environmental conditions, each sugar mill addresses the supply challenge from a particular perspective (Figure 2).



Figure 2. Comparison analysis of actions implemented by sugar mills to ensure sugarcane supply.

Sugar Mill A perceives the problem as a long-term phenomenon linked to production restructuring, a lack of generational continuity, and the weakening of loyalty of sugarcane growers toward other production options. The loss of cultivation area represents the end of long-term relationships historically built with producers, jeopardizing operational continuity. In response, this agribusiness (Sugar Mill A) has opted to implement a strategy centered on a supplier retention program that prioritizes administrative simplification, the use of digital media for timely communication, and investments in improved technical assistance and mechanization. It also includes close-service projects for producers and satisfaction surveys; furthermore, it contemplates the application of tailored financial incentives, advanced technical assistance, and preferential service for producers who supply large volumes.

In contrast, Sugar Mill B addresses the problem from the perspective of operational stability and competitive advantage over the other two mills. This industry recognizes that, in a highly competitive environment, logistical efficiency and speed of collection are as crucial as price or individual incentives. Therefore, it prioritizes retaining large producers, who control the majority of the supply and represent lower logistical costs per ton. To achieve this, it has established incentives such as tonnage bonuses, in-advance payments based on committed volume, and preferential shifts for harvesting and hauling. Furthermore, it organizes social events to improve perceptions within the community, strengthening a sense of belonging to the agribusiness. The strategy includes harvesting at the optimal age as a quality policy to avoid losses in the KARBE indicator (Standard base recoverable sugar kilograms) that protects supplier income.

On their part, Sugar Mill C interprets the supply problem as a strategic opportunity to differentiate from the competition through a close-service tailored approach. This sugar mill acknowledges its limited supplier base, so it prioritizes direct, trust-based relationships and personalized attention. This approach is attractive to producers who feel neglected or overlooked by other industries. Sugar Mill C strategy is geared towards attracting and consolidating new suppliers, especially those who value the availability of local offices, flexible terms, and streamlined processes. This agribusiness has simplified administration procedures, strengthening its territorial presence through service centers and comparative advertising campaigns with the aim of improving perception of producers.

Prospective scenarios

Based on prospective analysis, the influential, dependent, and environmental variables with the greatest impact on the regional sugarcane system were identified. Production, technical, economic and institutional factors were considered. Among the statements with the greatest differential impact that that outstand on influence from one scenario to another, we identified the value of KARBE as an indicator of sugarcane yield ratio, which is considered decisive for supplier loyalty toward an agribusiness and is associated with producer profitability. Also, crop diversification, as a strategy reflecting the producer tendency to diversify agricultural activity as a means of increasing family income; irrigation and constant renewal, which have a high influence on sustainable consolidation due to their close relationship with productivity; and simplification in administration procedures,

as part of the supplier retention strategy to improve the perception of producers to agribusinesses.

Despite representing different trajectories that may not be mutually exclusive, these three sugar mills agree that productive intensification is the main axis for maintaining the profitability and competitiveness of sugarcane cultivation. In order to show how the relationships among the statements from these agribusinesses are structured, a graph on the influence vs. dependence function was generated, as a map which served as the basis for constructing the prospective scenarios (Figure 3).

Based on the identified elements, three scenarios were constructed that project opportunities and decisions that could influence the regional course of the sugarcane production system in the coming years. In the “Sustainable consolidation scenario”, sugarcane remains as the dominant option. Priority is given to supplier retention and technological adoption is promoted, green harvesting, and intensification practices compatible with a sustainable model. Intensification is a gradual process driven by the adoption of technological innovations, plant varieties renewal, and the efficient use of production resources.

The “Competition and adaptation scenario” describes the persistence of a high-pressure environment caused by production restructuring toward alternative crops. This forces agribusinesses to adapt their strategies, explore new incentives, and improve logistics efficiency. Intensification is key to reducing costs, increasing productivity per hectare, and retaining producers who prioritize efficiency and production competitiveness. Finally, the scenario for “Sugarcane recovery in the face of an agave crisis” suggests a partial or

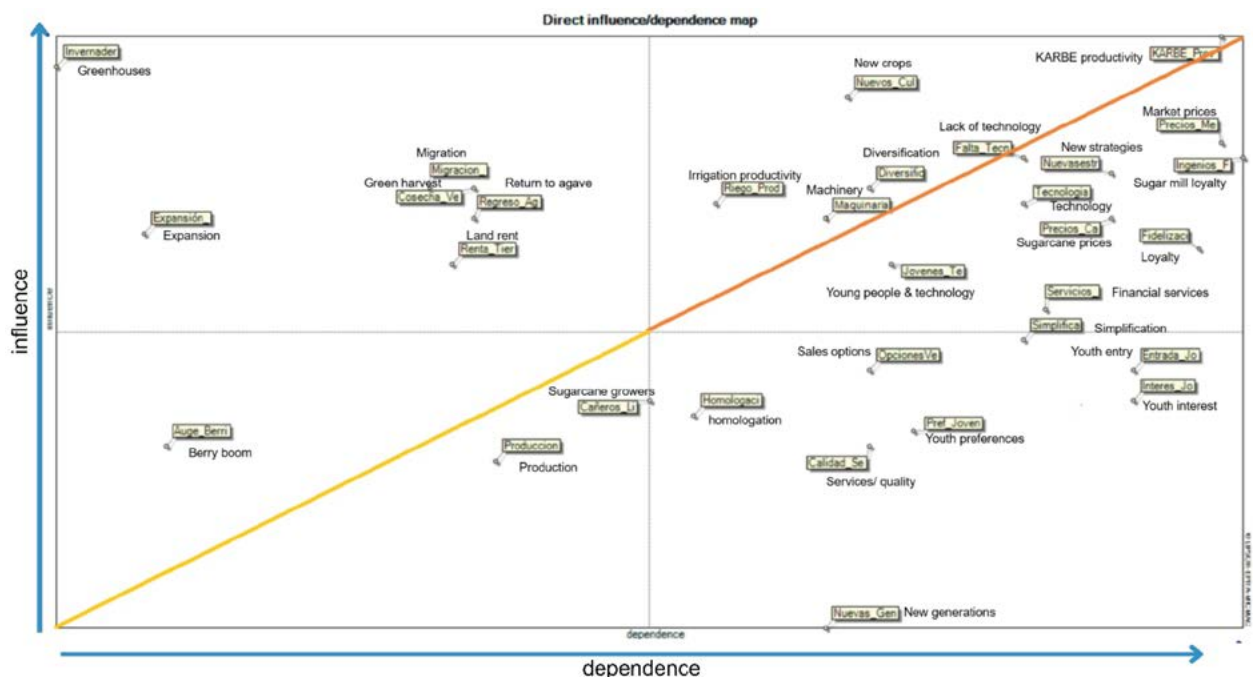


Figure 3. Map of influence vs. dependence of the identified statements for the future of sugarcane production and supply management.

total return of cultivation area to sugarcane due to the decline in agave profitability. This reincorporation requires favorable profitability conditions and support, through intensive technical management, sugarcane varieties renewal, and logistics efficiency. Intensification is the means to ensure a return as part of a new production stage with improved conditions.

Although each scenario responds to different contexts, they all require key conditions for restructuring or continuation in sugarcane cultivation, showing how to give direction to the role of intensification (Table 2).

While an extensive expansion could be considered an option to ensure supply, according to the Institute of Statistical and Geographic Information in Jalisco (IEEG Jalisco, 2018), this region already has virtually all agricultural lands occupied by crops such as sugarcane, agave, maize, chili peppers, among others. Therefore, adding new hectares of sugarcane would require conversion processes from other agricultural uses. Additionally, another factor limiting the expansion of the cultivated area is water availability, as the crop requires approximately 1500 mm of annual rainfall for optimal development (CONADESUCA, 2015). However, the average annual rainfall is around 930 mm, making supplemental irrigation essential (IEEG Jalisco, 2023).

Conditions for productive intensification

The main approach to intensification is based on the analysis of various arguments; former Mexico's Secretariat of Agriculture and Rural Development-SADER (2023) mentioned that the average sugarcane yield of the state of Jalisco was around 84 Mg ha⁻¹ in 2023. However, CONADESUCA (2016) stated that the varieties most commonly used in Mexico (CP72-2086 and Mex 69-290) can achieve a potential average yield of 115 and 200 Mg ha⁻¹, provided that the agronomic management is optimal. This means there is room to improve productivity through the adoption of technological innovations, technical support, and new agricultural practices, such as plant renewal, precision agriculture, irrigation modernization, among others. There are also conditions that compromise the full utilization of productive potential. García-Preciado *et al.* (2017) indicated that in Jalisco, approximately 50% of the sugarcane acreage depends on two varieties that have been used for more than 30 years. The reduced genetic diversity and a low rate of seedling renewal

Table 2. Prospective scenarios of the sugarcane production system; environment, productive response and the role of intensification.

Scenario	Main environmental driver	Producer behavior	Role of intensification
Sustainable consolidation	Coordination and support from actors within the sugarcane system	Gradual intensification and long-term permanence in sugarcane cultivation	As part of a planned and gradual strategy
Competition and adaptation	Competitive pressure from alternative crops	Partial production restructuring toward alternative crops	Becomes necessary to maintain profitability and competitiveness
Recovery following the agave crisis	Decline in the profitability of agave cultivation	Partial or total return to sugarcane	Key to capitalizing on returning producers and attracting new ones

have led to a decrease in sugarcane yield and quality. Vegetative material used for seedling renewal mostly comes from commercial crops without formal certification protocols or systematic use of seedbeds (Aquino *et al.*, 2021; Reyes-Hernández *et al.*, 2022).

In addition to agronomic and genetic improvements, it is important to consider that increased production requires addressing operational aspects related to the efficient logistics of cutting and transport to the mill. Efficiency during harvesting directly influences yield both in field and sugar mill (Palacios-Vélez *et al.*, 2011). Proper scheduling of cutting operations and effective transport management reduce downtime between harvesting and arrival at the mill, thus preventing losses of freshness that negatively impact industrial yield. Those authors also suggest incorporating information systems to monitor and coordinate the harvest in real time, achieving more efficient logistics and precise operational decisions.

While increased production is the common thread running through the possible scenarios and strategies to be implemented, their success depends largely on the ability to adapt to the diverse realities of the producer profiles conforming the supply system. Due to there are marked differences in levels of technology, technical capabilities, motivations, and even organizational structures. For intensification to effectively contribute to the competitiveness and sustainability of sugarcane crop, it should be implemented through differentiated intervention schemes tailored to each type of producer.

Possible strategic interventions differentiated by profile

Small-scale sugarcane farmers (Social growers) can benefit from the application of basic technologies, as it was demonstrated with a model applied to small and medium-sized sugarcane farms, where yields were improved through soil conservation practices, localized fertilization, and green harvesting (Castelán-Estrada *et al.*, 2016). This model includes support and practical training to foster the building of improved agronomic skills. Functional associations can also be incorporated, including the collective purchase of inputs at preferential prices, the management of demonstration plots to replicate practices under similar conditions, and the shared use of machinery, thereby improving territorial integration and individual productivity.

For Stable sugarcane growers operating under traditional methods and exhibiting low technological adoption, yields can be improved through practical, easy-to-implement, and low-cost solutions; such as improving soil structure and nutrient absorption through the incorporation of organic matter; proper waste management, or the localized application of phosphate fertilizers (SAGARPA, 2009; IICA, 2019).

In a subsequent report, SAGARPA (2009) also suggested that producers with these characteristics be served through agricultural extensionists with modular technical support, the use of technical assistance teams, and agreements with sugar mills. This would provide support in improving practices that could increase yields without creating greater challenges. On their part, Fideicomisos Instituidos en Relación con la Agricultura-FIRA (2009) proposed a land consolidation plan that would group nearby plots belonging to different owners to reduce operation costs for services such as mechanization.

The Diversifying sugarcane growers present an intermediate profile in terms of technological use and openness to innovation. Therefore, it is recommended to implement

technology transfer mechanisms and technical support without compromising its profitability. According to Mejía *et al.* (2010) and Castelán-Estrada *et al.* (2016), training, monitoring economic results, and establishing demonstration plots, that allow visualization of the benefits of improving productive efficiency from the supplier perspective, are usually appropriate for this profile. FIRA (2009) and SAGARPA (2007) added that the incorporation of digital crop monitoring platforms, the scheduling of harvests, or the management of inputs; along with consolidated purchases of inputs and machinery, improved logistics, and varietal renewal, all contribute to reducing costs per hectare, which positively impacts profitability.

Specialized sugarcane growers represent a strategic profile for the sector due to their more business-oriented approach, higher yields, and openness to models with more advanced technology. IICA (2019) indicated that the implementation of technological packages with technical assistance improves the quality, volume, and regularity of sugarcane supply. Since this group shows favorable characteristics, their access to financing is facilitated, to develop business models and participate in the production of biofuels or fertilizers. Furthermore, they can play a key role in technology transfer processes to the other producer profiles through peer-learning and demonstration plots (SAGARPA, 2009).

Another factor to consider for the proper implementation of intervention strategies and the formulation of initiatives is to rely on a production base that reflects the actual structure of those involved in the supply system. One of the main challenges is recognizing areas for current improvement and assessing the need to supplement or build a database to focus services according to production capacities. Currently, the available registry is associated with the Governmental program “Produccion para el Bienestar” and the Mexican Social Security Institute (IMSS) that execute administrative functions, such as distributing subsidies and providing medical care, but do not allow for the identification of active sugarcane producers. According to this data, 94% of producers have a maximum of 5 hectares in sugarcane production, and only 4.42% belong to the Diversifying and Specialized groups, who are the ones with the greatest potential to improve the supply system. This record does not correspond to the reality observed in the field, but this discrepancy is explained by the fragmentation of agricultural lands to maximize access to government support.

Therefore, the initiative of the agro-industries is required to generate real records that allow the identification of true producer profiles, thus providing timely service, as a necessary condition to achieve a competitive and efficient sugarcane supply system.

CONCLUSIONS

This study confirmed that the sustainability of the sugarcane supply system in a highly competitive region will depend on how relationships with producers are established. Each producer profile expressed distinct motivations, scales, levels of loyalty, and technical capabilities. This diversity demonstrated that formulating universal acquisition and retention strategies is ineffective, because the real needs of each producer profile are not addressed.

Producers who respond mainly to social benefits were identified, but there are also profiles with higher productive potential, such as diversifying and specialized sugarcane growers. However, there are currently no indicators for the accurate evaluation of the results and impacts of the strategies. This contributes to the supply problems and weakens traditional governance.

The most immediate goal should be complementing and updating the National Registry of sugarcane growers to identify active producers, which allow creating tailored value propositions. In addition, the adoption of innovations is required, such as a complete and updated geo-referenced database of lands dedicated to sugarcane cultivation, in order to support an efficient supplier recruitment and retention of the younger producers who have the ability to revitalize the sector.

ACKNOWLEDGEMENTS

To the members of Mexico's National Committee for the Sustainable Development of Sugarcane (CONADESUCA), for their assistance in gathering sectoral information. To sugarcane producers, sugarcane organizations, and the technical staff of the sugar mills, for their essential collaboration for the development of this study.

REFERENCES

- Aquino Mercado, P. R., Peralta Jiménez, J., Valdez Castro, J. C., & Salvador Juárez, I. (2021). Determinantes de la productividad de caña de azúcar. Sistema de Información para la Integración del Balance Azucarero (SIIBA).
- Arango Morales, X. A., & Cuevas Pérez, V. A. (2012). Método de análisis estructural: matriz de impactos cruzados multiplicación aplicada a una clasificación (MICMAC). Tesis doctoral. Universidad Autónoma de Nuevo León.
- Cabrera Palafox, H. (2022). Elaboración de un instrumento de investigación con el método Delphi. Analizando el estrés y malestar en docentes universitarios. *IE Revista de Investigación Educativa de La REDIECH*, 13, e1364. https://doi.org/10.33010/ie_rie_rediech.v13i0.1364
- Castelán-Estrada, M., Salgado-García, S., Ortiz-Laurel, H., & Juárez-López, J. F. (2016). Transferencia del modelo de alta rentabilidad para la transformación integral del campo cañero en México. *Agro Productividad*, 9, 14-17.
- CONADESUCA. (2024). Padrón de productores de la zona de abasto Región valles. Histórico de informes: 11° Informe estadístico del sector agroindustrial caña de azúcar en México (zafras 2013-2014/2023-2024). Variedades con mejores rendimientos de las zonas cañeras en México. Ficha técnica del cultivo de la caña de azúcar.
- CONADESUCA. (2016). Variedades con mejores rendimientos de las zonas cañeras en México (pp. 1–7). https://www.gob.mx/cms/uploads/attachment/file/114367/Nota_Informativa_Febrero_2016_Variedades_con_Mejores_Rendimientos_de_las_Zonas_Ca_eras_en_M_xico.pdf#:~:text=2010,mx
- CONADESUCA. (2015). Ficha técnica del cultivo de la caña de azúcar. SAGARPA. https://www.gob.mx/cms/uploads/attachment/file/141823/Ficha_T_cnica_Ca_a_de_Az_car.pdf
- FAO & BID. (2007). Restricciones y oportunidades. In: F. Soto Baquero, M. Rodríguez Fazzone, & C. Falconi (eds.) Políticas para la agricultura familiar. Organización de las Naciones Unidas para la Alimentación y la Agricultura y Banco Interamericano de Desarrollo (pp. 16-18).
- FIRA-Fideicomisos Instituidos en Relación con la Agricultura. (2009). Competitividad de la industria del azúcar en México.
- García-Preciado, J. C., Álvarez-Cilva, M., Guzmán-Martínez, M., Cervantes-Preciado, J. F., & Bermúdez-Guzmán, M. J. (2017). Evaluación de variables de calidad en híbridos de *Saccharum* spp. en diferentes ambientes agroecológicos de Jalisco, México. *Agroproductividad*, 10(11), 105-106.
- Ghezzi, P., Stein, E., Ordoñez, R., & Cornick, J. (2022). Una puerta a las cadenas agroalimentarias globales para los pequeños productores. In *Competir en la agroindustria. Estrategias empresariales y políticas públicas para los desafíos del siglo XXI*. Banco Interamericano de Desarrollo. 283 p.

- Gobierno del Estado de Jalisco. (2023). Agenda regional Lagunas (pp. 15-22). https://plan.jalisco.gob.mx/wp-content/uploads/2023/06/11-Lagunas-Agenda-Regional_final-V3.pdf
- Godet, M. (2000). El arte de escenarios y planificación estratégica: Herramientas y trampas. Marcombo.
- Gómez-Merino, F. C., Trejo-Téllez, I. L., & Aguilar-Rivera, N. (2021). Agregación de valor y diversificación de la agroindustria de la caña de azúcar en México: Opciones y desafíos. *ATAM*, 34(2), 6-10.
- IICA-Instituto Interamericano de Cooperación para la Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. (2019). Agenda de innovación intersectorial para el desarrollo agroindustrial de la caña de azúcar para Oaxaca, San Luis Potosí y Veracruz. *Sustainability (Switzerland)* 11(1): 1-14.
- IIEG Jalisco-Instituto de Información Estadística y Geográfica de Jalisco. (2018). Diagnóstico de la región Valles (pp. 44-46). https://iieg.gob.mx/contenido/Municipios/10_valles_diagnostico.pdf#:~:text=El principal producto del sector,9
- IIEG Jalisco-Instituto de Información Estadística y Geográfica de Jalisco. (2023). Diagnóstico de la Región Valles (p. 51).
- Mejía S., E., Rivera A., J. C., Oviedo N., E., Debernardi D. V., H., & Tiscareño L., M. (2010). Estudio de caracterización de zonas potenciales de mecanización en las zonas de abasto cañeras. Colegio de Postgraduados, SAGARPA.
- Palacios-Vélez, O. L., Mejía-Sáenz, E., Piñón-Sosa, L., & Sánchez-Hernández, H. (2011). La frescura de la caña de azúcar: Un caso de estudio en tres ingenios de México. *Agrociencia* 45(7), 831-847.
- Reyes-Hernández, J., Coronado-Blanco, J. M., Bosque, L. Á. R., Khalaim, A. I., Estrada-Drouaillet, B., Torres-Acosta, R. I., & Reséndiz-Ramírez, Z. (2024). Efecto del estrés hídrico en el barrenador (*Eoreuma loftini* Dyar) y la caña de azúcar (*Saccharum officinarum* L.). *Acta Agrícola y Pecuaría* 10(1), e0101005.
- SADER-Secretaría de Agricultura y Desarrollo Rural. (2023). SADER Jalisco refuerza acciones para la cosecha de caña en verde (Junio 1º). <https://sader.jalisco.gob.mx/prensa/noticias/sader-jalisco-refuerza-acciones-para-la-cosecha-d>
- SAGARPA– Secretaría de Agricultura, Ganadería, Recursos naturales, Pesca y Alimentación. (2009). Histórico de informes. Programa Nacional de la Agroindustria de la Caña de Azúcar. Desarrollo de un modelo integral de sistema de información geográfica y edáfica como fundamento de la agricultura de precisión en la caña azúcar. Proyecto nacional de alta rentabilidad para el reordenamiento y transformación del campo cañero mexicano.
- SAGARPA. (2007). Programa Nacional de la Agroindustria de la Caña de Azúcar. <http://www.conadesuca.gob.mx/eficienciaproductiva/PRONAC.pdf>
- SIAP-Servicio de Información Agroalimentaria y Pesquera. (2024). Superficie sembrada con agave 2018-2023. http://nube.agricultura.gob.mx/avance_agricola/
- Susilowati, K. D. S., Rachmi, A., & Riwijanti, N. I. (2020). Creating a sustainable supply of sugarcane through contract farming partnership (A case study at sugar factory “Kebon Agung”, Malang-Indonesia). *International Journal of Supply Chain Management* 9(3), 117-128.

Stakeholders and producers in the strawberry value chain: Perceptions and key challenges in Mexico's Bajío region

Bojorges-Muñoz, Vanessa¹; Martínez-González, Enrique G.^{1*}; Aguilar-Ávila, Jorge¹; Lucio-Mendiola, Adriana Y.¹

¹ Universidad Autónoma Chapingo. Centro Académico y de Investigaciones Económicas, Sociales, y Tecnológicas de la Agroindustria y Agricultura Mundial. Km 38.5 Carretera México-Texcoco, Texcoco de Mora, Estado de México, México. C.P. 56230.

* Correspondence: enriquemartinez@ciestaam.edu.mx

ABSTRACT

Objective: To analyze the relationships, current perspectives, and expectations of stakeholders and producers engaged in the strawberry value chain in the municipalities of Maravatío and Tarandacua, considering environmental, social, and economic aspects, with the aim of understanding the challenges and future of strawberry production in this important producing area.

Design/methodology/approach: Semi-structured interviews were conducted with stakeholders, focusing on three dimensions: their role and relationship with producers, perspectives on the sector, and their vision for the future. Producers completed a Likert-type survey on their environmental, social, and economic perceptions. The information was then transcribed, and relevant ideas, concepts, and patterns in the interviewees' narratives were identified.

Results: Stakeholders believe that the sustainability of the value chain depends on investment in technology, resource management, adaptation to climate change, and the adoption of innovations that improve production. However, producers do not usually consider environmental issues, but rather economic and social ones.

Limitations on study/implications: The small size of the stakeholder group limits the generalizability of the findings to other similar contexts.

Findings/conclusions: Although the activity has boomed and consolidated both nationally and regionally, it faces structural constraints such as climate variability, water availability, lack of logistics infrastructure, the presence of pests and diseases, and the need to standardize production practices. This could limit the long-term sustainability of production.

Keywords: sustainable agriculture, agri-food chain, strawberry production.

Citation: Bojorges-Muñoz, V., Martínez-González, E. G., Aguilar-Ávila, J., & Lucio-Mendiola, A. Y. (2026). Stakeholders and producers in the strawberry value chain: Perceptions and key challenges in Mexico's Bajío region. *Agro Productividad*. <https://doi.org/10.32854/ctz1sx85>

Academic Editor: Jorge Cadena Iniguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: August 27, 2025.

Accepted: January 15, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 163-172.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Strawberry production in Mexico is considered an activity of high economic importance due to its intensive use of labor, not only at the production level but also in the industrial sector. In addition, it is linked to a high demand for inputs, marketing, and transportation, among other activities (Echánove Huacuja, 2001). Mexico leads strawberry production in



Latin America, with an output of 541,552 t, followed by Brazil, Colombia, Argentina, and Peru (FAO, 2023). In Mexico, the most important growing areas are located in Michoacán, Baja California, Guanajuato, Jalisco, and the State of Mexico (SIAP, 2023). The rapid growth in strawberry demand has been supported by advanced technologies, improved production practices, as well as genetic breeding programs (Agehara *et al.*, 2020). However, production also faces challenges such as climate variability, high use of agrochemicals and water, labor shortages, and land availability (Samtani *et al.*, 2019). In this context, value chain (VC) analysis has gained increasing importance in agri-food research. Rojas Rojas & Valencia Sandoval, (2022) mention that the description of a VC provides a detailed view of its functioning, examining in depth who the direct and indirect participants are, their roles, the market segments they target, the supporting services, and the governance dynamics that regulate its operation.

However, Liverpool-Tasie *et al.*, (2020) point out that there is a hidden link in agri-food value chains, such as food processors, wholesalers, and logistics companies, which, although they represent 40% of the VC, are often overlooked. This is despite the fact that they constitute the closest connection between small-scale producers and the market, and can encourage the adoption of sustainable practices, as well as contribute to higher producer incomes. This is the case in the study area, where an agro-industry identified the opportunity to incorporate small-scale producers into its value chain, generating a social impact and highlighting long-term productive and sustainability potential through the transmission of RA (regenerative agriculture) practices and the adoption of technologies.

The sustainable transition of food systems can be achieved through contract farming, as agro-industries facilitate the dissemination of climate-smart practices and technologies and enable small-scale farmers to meet phytosanitary, quality, and sustainability standards (Schoneveld & Weng, 2023).

In the specific case of strawberries, the main production-level challenges include extreme climatic conditions, the presence of pests and diseases, consumer preferences regarding quality, and labor shortages. Therefore, as strawberry demand continues to increase, production methods must adapt by incorporating new production systems and technologies (Hernández-Martínez *et al.*, 2023). This can be achieved through the interaction between producers and stakeholders; however, despite their importance, stakeholders' perspectives on current production have been poorly documented, as studies usually focus on the producer link of the value chain.

The main reasons for collaboration in agricultural value chains are to improve market access and product quality, and these collaborations are facilitated and encouraged when supported by governmental and non-governmental entities (Mishra *et al.*, 2024). For example, collaboration with research institutions has enabled the development of pest-resistant varieties. Integration with marketing-related stakeholders allows market diversification and brings producers closer to improved production practices as well as certification schemes, while input suppliers promote innovations and the adoption of technologies that increase productivity.

In the case of Mexico, it is crucial to promote collaboration with small-scale strawberry producers in order to address challenges such as the lack of financial infrastructure,

specialized machinery for harvesting, sorting, packing, and labeling, as well as the absence of purchase contracts, agricultural insurance, and compliance with export standards (Zamora Torres & Baez Figueroa, 2022).

The literature suggests that the establishment of new organizational mechanisms with the potential to facilitate knowledge transfer constitutes the basis of systemic approaches grounded in Agricultural Knowledge and Innovation Systems (AKIS). These systems play a key role in knowledge transfer and the adoption of innovations, involving scientific institutions, public and private entities, technical advisors, and farmers (Masi *et al.*, 2022).

This study analyzes the relationships, current perspectives, and expectations of stakeholders and producers involved in strawberry production in the municipalities of Maravatío and Tarandacuao, located in the states of Michoacán and Guanajuato, respectively. Environmental, social, and economic aspects are considered in order to understand the challenges and future of strawberry production in this important producing region.

MATERIALS AND METHODS

The research was conducted through semi-structured interviews with five stakeholders involved in strawberry production in the municipalities of Maravatío and Tarandacuao, located in the states of Michoacán and Guanajuato (Figure 1). Stakeholders were selected through convenience sampling, considering the connections that producers had with them, their relevance in the sector, and their availability to provide information. To ensure representation of different roles in the activity, the sample included participants from fresh produce marketing, a fruit and vegetable processing agro-industry, a technical advisor affiliated with an NGO, the manager of a RA program, and an input supplier.

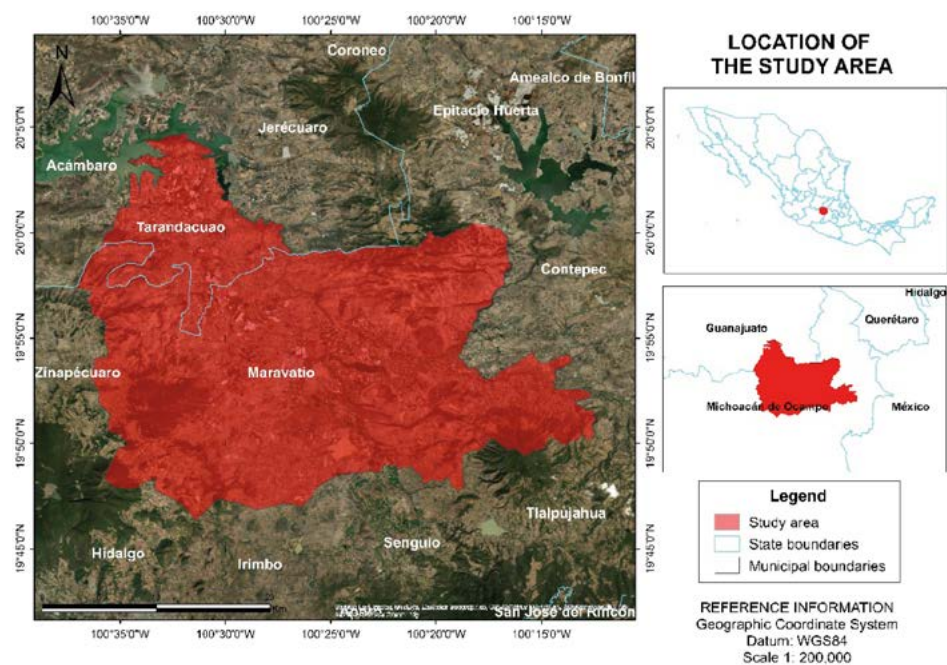


Figure 1. Spatial delimitation of the study.

In addition, a survey was administered to 30 small-scale strawberry producers participating in this program. The survey consisted of 15 items: 5 related to social identification, 5 to environmental aspects, and 5 to economic aspects. Perception variables were measured using a three-point Likert scale, with the following equivalence: 1 = disagree, 2 = neither agree nor disagree, and 3 = agree.

The selection allowed exploration of how stakeholders perceive their interactions with producers, their perspectives on the sector, and their views on the future of production in the area. Given the small number of interviews, priority was given to the depth of information obtained. Malterud *et al.*, (2016) note that qualitative interviews can shift the focus from the number of participants to the contribution of new knowledge derived from analysis. In this sense, the greater the relevance and quality of the information available for the study, the lower the need for a large number of participants. Therefore, the results should be interpreted as part of an exploratory study, paving the way for future research aimed at including a greater number of stakeholders per area, as well as stakeholders who were not initially considered.

The interviews were conducted from July to September 2024, with each interview lasting approximately 90 minutes. Interviews were carried out both in person and online, and were recorded with the stakeholders' consent, who were informed of the research objectives and the importance of their participation.

The interview guide was designed based on literature on value networks and structured around three main pillars: 1) the role and relationship of stakeholders with strawberry producers; 2) perceptions of the current production situation; and 3) perspectives and strategies for the future. This approach allows understanding not only the role of each stakeholder but also the sustainability of the sector.

Each interview was transcribed, and the data were subsequently coded so that each element received a representative attribute capturing the essence of the interviews. In a second step, the codes were reviewed and organized to identify patterns within each interview and to structure all relevant data (Saldaña, 2013). Stakeholder anonymity was ensured by assigning a general description of their role, avoiding the use of the interviewee's name or the company where they work (Table 1).

For the surveys, the data obtained were organized and processed in Excel[®] for Microsoft 365. Absolute frequencies were calculated for each response category of each

Table 1. Characterization of interviewed and surveyed stakeholders.

Actor	Position/role	Relationship with producers
Fresh strawberry marketer	Supply Manager	Direct purchase of fresh strawberries
Agroindustry	Project Manager	Regenerative agriculture project management
NGO	Project Manager	Regenerative agriculture project management
NGO	Agricultural coordinator	Technical advice
Input supplier	Independent consultant	Technical advice
Producers	Strawberry growers (30)	Primary production

item. This analysis allowed the distribution of producers' perceptions regarding each item to be identified.

RESULTS AND DISCUSSION

Role and Relationship with Producers

Stakeholders agreed that the strawberry value chain in the region involves stakeholders who add value and increase the efficiency of production processes. The agronomist coordinator of the NGO highlighted the importance of supporting producers in the implementation of good agricultural practices, as this not only results in high-quality fruit but also improves the producers' position in the market. Additionally, they emphasized that:

“Technical monitoring allows producers to comply with food safety standards and obtain better prices for their fruit.”

On the other hand, the fresh fruit buyer considers that their relationship with producers is direct and based on trust, ensuring that the company they work for has a consistent supply of fresh, high-quality strawberries. In this sense, although producers export through intermediaries, long-term personal relationships are a fundamental pillar in the integration of the value chain. In this regard, Pham & Anh, (2024) mention that there are two stages in the buyer-supplier relationship: the first is the initial stage, formed through empirical evidence and relational evaluation, and the second is a maturation stage, in which trust is maintained through emotional ties and personal experiences.

The agro-industry emphasizes its relevance in the chain by transforming and processing fruit that is not marketed fresh, adding value to the product and ensuring food safety before distribution. As Schoneveld, (2022) notes, inclusive agro-industries that connect small-scale farmers help mitigate coordination difficulties as well as improve access to inputs and markets.

One of the most important links in the agri-food supply chain lies at the interface between farms and agro-industries, as this is the source of the raw materials necessary to produce the current range of food products for human consumption. A significant portion of the environmental impact at this point is due to the use of agrochemicals, water, land, and energy associated with agriculture. For this reason, there is interest in both sustainable agricultural practices and the transition to RA (Miranda-Ackerman *et al.*, 2019)

Consequently, the NGO and the agro-industry have implemented an RA program with a group of small-scale producers. The NGO acts as a facilitator and coordinator, connecting producers with buyers, providing training on sustainable value chains, and offering technical support in the implementation of practices that enable this goal. The NGO considers that through its activities, information asymmetries are reduced and producers are kept informed about the quality standards required by the markets.

Perspectives on Strawberry Production in the Area

Stakeholders agree that strawberry production in the area has experienced growth in recent years, driven by both national and international demand. However, they are aware that this rapid growth is not without challenges, such as the availability of inputs, the current climate variability, water scarcity due to its irrational use in this and other crops in the region, as well as logistical and transportation difficulties that hinder producers' ability to adapt to current demand.

The coordinator of the organization emphasizes that:

“Producers face challenges in quality standardization, but the training programs implemented through the program have significantly improved their performance.”

Additionally, he emphasizes that technical training and continuous monitoring of producers are of utmost importance, so that they adopt not only the practices but also the technologies promoted by the program. Currently, producers lack awareness of the proper management of pesticides and fertilizers and tend to use them excessively, as well as water, due to inefficient irrigation control. However, producers do not perceive it this way, as 66.6% of participants report that they implement appropriate practices for pesticide and fertilizer management and application.

Regarding water resources, 46.6% of producers consider that there are effective measures for water conservation in production areas, and 33.3% disagree that strawberry production contributes to the depletion of local water resources (Figure 2). Romero-Gómez & Suárez-Rey (2020) mention that measures should be taken to improve environmental performance, such as optimizing fertilizer use through systems that support decision-making on soil nutrient management, accompanied by training programs for producers.

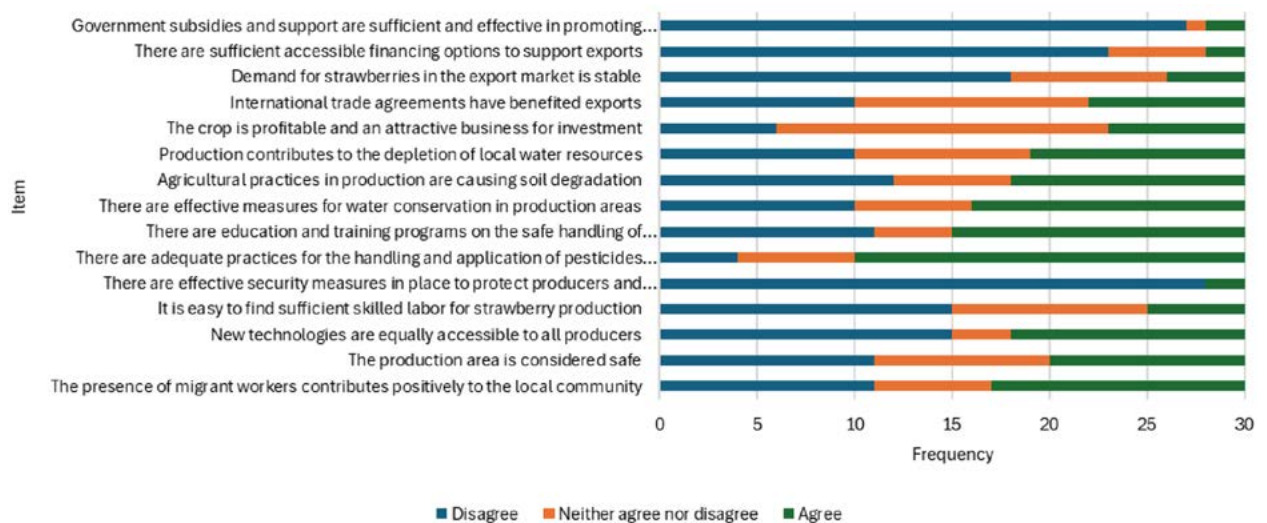


Figure 2. Economic, environmental, and social perceptions of producers. *The first five items refer to the economic dimension, followed by the environmental items, and finally the social items.

In addition, efficient water-use strategies should not only be directed at production practices, but also involve the agro-industry promoting sustainability programs within the value chain. Cano-Gómez *et al.*, (2025) note that increasing difficulties arise from freshwater scarcity and the high generation of agro-industrial waste, particularly that derived from fruit and vegetable processing.

For its part, the agro-industry added that the adoption of technologies that ensure uniformity and food safety is an indispensable requirement for accessing more competitive markets at both the national and international levels. Producers recognize the need to adopt technologies and innovations in strawberry production; however, half of them mention that new technologies are not equitably accessible to all producers.

These findings relate to the concept of the “twin transition,” which seeks to link digital technologies with sustainable development, highlighting the importance of developing appropriate strategies aligned with the characteristics, objectives, and technological capacities of companies in order to overcome challenges in digitalization. This approach also emphasizes that the transition requires strategic guidance to manage technological expansion according to the nodes and stakeholders within the supply chain, since their scope and efficiency may limit or enhance the capacity to achieve sustainability and, consequently, the Sustainable Development Goals (Myshko *et al.*, 2024). In this sense, the results of the study show that the implementation of the “twin transition” in food value chains depends not only on the availability of technology, but also on the adoption capacity of small-scale producers.

Stakeholders highlight that relationships among themselves and with other stakeholders can directly influence the improvement of producers’ competitiveness. In this regard, Peña *et al.* (2008) mention that value chains in the agri-food sector must go beyond simple vertical integration, as they require coordinated efforts from all companies involved in the chain. In addition, the availability of information is vital at each link of the chain, as it allows stakeholders to identify changes in consumption trends. The objective of these dynamics is to increase product valorization by promoting added value through innovation.

For example, the fresh strawberry buyer mentioned that ensuring product quality from the field allows logistics planning and reduces losses from farm to table, which in turn guarantees market stability.

Future Perspectives in Production

Stakeholders identified opportunities to strengthen the strawberry value chain and ensure its long-term sustainability. These include crop diversification to maintain soil health, digitalization of marketing processes, and the opening of new international markets. The NGO’s technical advisor emphasizes that:

“The use of digital platforms allows producers to reach buyers who were previously inaccessible.”

Consequently, it is evident that the use of technology would help reduce the trade barriers faced by small-scale producers. On the other hand, significant structural challenges were

also mentioned, such as: water availability and climate variability affecting production cycles and fruit quality; limited access to inputs and specialized services necessary to improve production methods that ensure soil and environmental health; competition for land use due to the specialization of other crops; and the need for adequate infrastructure to reduce losses and maintain fruit quality.

Regarding the continuity of strawberry production in this area, opinions suggest that if producers maintain good production practices, the region will continue to be a reference for strawberry production at the national level. This aligns with Ilari *et al.* (2021) who indicate that by managing the type and quantity of pesticides used in production, residues can be minimized not only in the product but also in the soil, thereby obtaining a safer and more sustainable product, while also strengthening cooperation mechanisms among stakeholders.

However, they consider that the sustainability of the value chain depends on investment in technology, resource management, adaptation to climate change, and the adoption of innovations that improve production. To achieve the transition to sustainable agri-food value chains, the focus should be on improving agricultural practices and consumer food choices, making it necessary to integrate stakeholders situated between producers and consumers to act as active agents of this transformation (Barrett & Gómez, 2025).

Regarding the long-term continuity of producers, environmental issues are not usually prioritized; rather, economic aspects are considered. Currently, 60% of interviewees perceive that export market demand for strawberries is unstable, 76.6% indicate that there are few accessible financing options to support strawberry exports, and 90% consider that government subsidies and support are insufficient. In addition, they identify production-related problems linked to insecurity in production areas. Therefore, they consider it necessary to include other stakeholders and actions oriented toward the economic and social dimensions of sustainability (Figure 3).



Figure 3. Traffic-light diagram of thematic axes among stakeholders and producers.

CONCLUSIONS

The analysis of stakeholder interviews allowed the identification of their interactions with producers in the region. Each stakeholder performs differentiated but connected functions, as their role focuses on ensuring fruit quality, facilitating market access, and promoting practices and innovations that enable the sustainability of the value chain. Consequently, competitiveness in the sector depends not only on the producers but also on the coordination among stakeholders.

Although the activity has experienced growth and consolidation at both the national and regional levels, it faces structural constraints such as climate variability, water availability, lack of logistical infrastructure, the presence of pests and diseases, and the need to standardize production practices. These factors could limit long-term sustainability in production. Therefore, efforts should be combined to foster greater cooperation among all stakeholders involved in the sector, including government entities and others that can provide producers with access to financing. In addition, investment is needed in the adoption of sustainable practices and technologies that strengthen producers' technical skills. However, the future will not depend solely on knowledge transfer by stakeholders, but also on the adoption capacity of producers. Therefore, collective efforts are required to address environmental, organizational, and commercial challenges.

Understanding and recognizing the links within the sector is key to designing strategies that strengthen regional competitiveness and ensure its long-term sustainability. In addition, to achieve the objectives set by the NGO and the agro-industry, a series of tasks must be undertaken, including improving access to financing, promoting greater adoption of technologies and RA practices, incorporating biofertilizers and biostimulants, implementing efficient irrigation, rotating crops, and ensuring supplier commitment to the agro-industry. Furthermore, the establishment of associations and collaborative networks will help strengthen the adoption of good production practices without compromising yield, while improving marketing conditions.

REFERENCES

- Agehara, S., Lin, S. Y., & Kang, L. (2020). Strawberry Production and Markets in Taiwan: Challenges, Trends, and Outlook. *International Journal of Fruit Science*, 20, S2018–S2029. <https://doi.org/10.1080/15538362.2020.1851340>
- Barrett, C., & Gomez, M. (2025). Fostering healthy, equitable, resilient, and sustainable agri food value chains. *Agricultural Economics*, 56, 390-400. <https://doi.org/10.1111/agec.70007>
- Cano-Gómez, C. I., Wong-Arguelles, C., Hinojosa-López, J. I., Muñoz-Márquez, D. B., & Wong-Paz, J. E. (2025). Novel insights into agro-industrial waste: Exploring techno-economic viability as an alternative source of water recovery. *Waste*, 3(15). <https://doi.org/10.3390/waste3020015>
- Echánove Huacuja, F. (2001). Abastecimiento a la Ciudad de México: el caso de los pequeños productores de fresa de Guanajuato. *Investigaciones Geográficas*, 45, 128-148. <https://doi.org/10.14350/riig.59149>
- Hernández-Martínez, N. R., Blanchard, C., Wells, D., & Salazar-Gutiérrez, M. R. (2023). Current state and future perspectives of commercial strawberry production: A review. *Scientia Horticulturae*, 312, 111893. <https://doi.org/10.1016/j.scienta.2023.111893>
- Ilari, A., Toscano, G., Boakye-Yiadom, K. A., Duca, D., & Foppa Pedretti, E. (2021). Life cycle assessment of protected strawberry productions in central Italy. *Sustainability*, 13(9), 4879. <https://doi.org/10.3390/su13094879>
- Liverpool-Tasie, L. S. O., Wineman, A., Young, S., Tambo, J., Vargas, C., Reardon, T., Adjognon, G. S., Porciello, J., Gathoni, N., Bizikova, L., Galiè, A., & Celestin, A. (2020). A scoping review of market links

- between value chain actors and small-scale producers in developing regions. *Nature Sustainability*, 3(10), 799-808. <https://doi.org/10.1038/s41893-020-00621-2>
- Malterud, K., Siersma, V. D., & Guassora, A. D. (2016). Sample size in qualitative interview studies: Guided by information power. *Qualitative Health Research*, 26(13), 1753-1760. <https://doi.org/10.1177/1049732315617444>
- Masi, M., De Rosa, M., Vecchio, Y., Bartoli, L., & Adinolfi, F. (2022). The long way to innovation adoption: insights from precision agriculture. *Agricultural and Food Economics*, 10. <https://doi.org/10.1186/s40100-022-00236-5>
- Miranda-Ackerman, M. A., Azzaro-Pantel, C., Aguilar-Lasserre, A. A., Bueno-Solano, A., & Arredondo-Soto, K. C. (2019). Green supplier selection in the agro-food industry with contract farming: A multi-objective optimization approach. *Sustainability*, 11(24). <https://doi.org/10.3390/su11247017>
- Mishra, V., Ishdorj, A., Tabares Villarreal, E., & Norton, R. (2024). Collaboration in agricultural value chains: a scoping review of the evidence from developing countries. *Journal of Agribusiness in Developing and Emerging Economies*, August 2025, 2044-0839. <https://doi.org/10.1108/JADEE-12-2023-0311>
- Myshko, A., Checchinato, F., Colapinto, C., Finotto, V., & Mauracher, C. (2024). Towards the twin transition in the agri-food sector? Framing the current debate on sustainability and digitalisation. *Journal of Cleaner Production*, 452, 142063. <https://doi.org/10.1016/j.jclepro.2024.142063>
- Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO). (2023). Value of Agricultural Production. <https://www.fao.org>
- Peña, Y., Nieto Alemán, P. A., & Díaz Rodríguez, F. (2008). Cadenas de valor: un enfoque para las agrocadenas. *Equidad y Desarrollo*, 9, 77-85. <https://doi.org/10.19052/ed.279>
- Pham, T. X. T., & Anh, N. N. (2024). The impact of trust on opportunism across different stages of buyer-supplier relationships: A process perspective. *Operations and Supply Chain Management*, 17(4), 367-383. <https://journal.oscm-forum.org/publication/article/the-impact-of-trust-on-opportunism-across-different-stages-of-buyer-supplier-relationships-a-process>
- Rojas Rojas, M. M., & Valencia Sandoval, K. (2022). Componentes clave de las cadenas de valor, un enfoque agroalimentario y sostenible. In *Competitividad en las cadenas de valor agroalimentarias conceptos y herramientas metodológicas*. (pp. 13-27).
- Romero-Gómez, M., & Suárez-Rey, E. M. (2020). Environmental footprint of cultivating strawberry in Spain. *International Journal of Life Cycle Assessment*, 25(4), 719-732. <https://doi.org/10.1007/s11367-020-01740-w>
- Saldaña, J. (2013). An introduction to codes and coding. In *The coding manual for qualitative researchers* (pp. 1-40).
- Samtani, J. B., Rom, C. R., Friedrich, H., Fennimore, S. A., Finn, C. E., Petran, A., Wallace, R. W., Pritts, M. P., Fernandez, G., Chase, C. A., Kubota, C., & Bergefurd, B. (2019). The status and future of the strawberry industry in the United States. *HortTechnology*, 29(1), 11-24. <https://doi.org/10.21273/horttech04135-18>
- Schoneveld, G. C. (2022). Transforming food systems through inclusive agribusiness. *World Development*, 158, 105970. <https://doi.org/10.1016/j.worlddev.2022.105970>
- Schoneveld, G. C., & Weng, X. (2023). Smallholder value creation in agrifood chains: Value network approach. *Land Use Policy*, 131, 106676. <https://doi.org/10.1016/j.landusepol.2023.106676>
- SIAP. (2023). Producción anual agrícola. <https://www.gob.mx/siap>
- Zamora Torres, A. I., & Baez Figueroa, I. (2022). Profitability and comparative advantage: Analysis of strawberry production in Michoacán, Mexico. *Agro Productividad*, 89-97. <https://doi.org/10.32854/agrop.v15i9.2233>

Profitability and comprehensive competitiveness of grain maize in a municipality in economic transition

Ibarra-Hernández, José M.¹; Valdivia-Alcalá, Ramón^{1*}; Contreras-Castillo, José M.¹; Hernández-Ortiz, Juan¹

¹ Universidad Autónoma Chapingo, carretera federal México-Texcoco, km 38.5, Texcoco, Estado de México, México. C.P. 56230.

* Correspondence: ramvaldi@gmail.com

ABSTRACT

Objective: to evaluate the private, social and environmental profitability and competitiveness of the production systems of native (Creole) and improved (modified) grain maize in rainfed and irrigated regimes in San José de Gracia, Aguascalientes.

Design/Methodology/Approach: for data collection, participant observation techniques, surveys and official sources from Mexico's National Foreign Trade Information System (SNICE), and the Tax Revenue Administration Service (SAT) were applied. A specific questionnaire was designed for grain maize producers in San José de Gracia to record inputs and production costs. Environmental (reduction of agrochemicals) and private assessments were performed with the Policy Analysis Matrix (MAP) methodology. The social analysis was based on the SAGARPA-FAO methodology for intermediate inputs, considering variables such as tariffs, taxes, inputs, subsidies, insurance-freight costs, transport costs, fuel prices and exchange rate.

Results: a 64.9% of grain maize production was profitable, competitive, and efficient. The presence of agricultural policies and market distortions improved profitability by 37.43% and competitiveness by 12.08% of grain maize production. On the other hand, these indicators were reduced by 20% and 5.3% when implementing environmental strategies.

Findings/Conclusions: at market and economic prices, the improved grain under irrigation presented the highest profitability and the Irrigated Creole system, the greatest competitiveness. In the environmental analysis, the Creole grain maize production system under irrigation showed competitiveness and profitability. However, these indicators were below the values assessed at private costs.

Keywords: sustainability, agricultural policy, private cost, social cost, environmental cost.

Citation: Ibarra-Hernández, J. M., Valdivia-Alcalá, R., Contreras-Castillo, J. M., & Hernández-Ortiz, J. (2026). Profitability and comprehensive competitiveness of grain maize in a municipality in economic transition. *Agro Productividad*. <https://doi.org/10.32854/hmb80981>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: August 29, 2025.

Accepted: January 23, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February, 2026. pp: 173-181.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

The production of grain maize in Mexican agriculture presents a constant dynamism in the technological, organizational and competitive spheres, moreover after the commercial opening of Mexico in 1994 (De Grammont, 2010; González & Alferes, 2010). This crop has not only been fundamental for food security, but also a central element in the construction of the country's cultural identity. Along these lines, Mexico's Secretariat of Agriculture



and Rural Development (SADER, 2023) emphasized that maize, in addition to being a staple in the national diet and a cultural reference, constitutes a strategic component of the Mexican economy.

However, the use of some production inputs in agriculture, such as commercial agrochemicals, has negative impacts on the environmental system (del Puerto *et al.*, 2014), which compromises the productivity and profitability of the sector in the short, medium and long term.

During the first two decades of the twenty-first century, the state of Aguascalientes experienced economic growth driven by a transition to industrialization, with special dynamism in the automotive sector (López, 2017). This process had a direct impact on agriculture activities, as the population employed in the primary sector decreased from 6% of the state total in 2013 to 3.8% in 2024 according to Mexico's National Institute of Statistics and Geography (INEGI, 2014, 2025). In contrast, employment in the manufacturing sector registered a 2.2% increase in the same period, which reflects a progressive transfer of the rural labor force to this sector. As a result, a growing desertion from agriculture was observed, with negative effects on the profitability of grain maize production in the municipality of San José de Gracia.

Another relevant phenomenon was the economic diversification of some producers towards religious tourism, based on the declaration of San José de Gracia as a Magical Town (Vargas & Rodríguez, 2021). This reorientation reduced attention to agricultural production processes and drove a 62% decrease in the area planted with grain maize. Grain yield decreased from 3594 ha⁻¹ in 2014 to 1366 ha⁻¹ in 2024, according to Mexico's Agrifood and Fisheries Information Service (SIAP, 2025). Such a reduction impacted both the profitability and competitiveness of producers dedicated to this crop.

Currently, agriculture develops within the framework of an international trade network. This requires the implementation of strategic policies that promote sustainable production at the local and national scales. In this context, to provide a comprehensive evaluation of the current situation of grain maize production, providing farmers and agricultural policymakers with well-founded arguments to identify opportunities that improve profitability and competitiveness for this crop, the objective of this research was to evaluate the private, social, and environmental profitability and competitiveness of the production systems of native (Creole) and Improved (modified) grain maize in rainfed and irrigated regimes in San José de Gracia, Aguascalientes.

MATERIALS AND METHODS

The research was conducted in the municipality of San José de Gracia, Aguascalientes, under a semi-humid temperate climate in the western zone and a temperate semi-dry climate in the remaining semi-flat zone, at an average 17 °C annual temperature (INEGI, 2024a).

The sample size was determined by applying the formula developed by Aguilar (2005), which is based on the calculation for finite populations, guaranteeing municipal representativeness.

$$n = \frac{Z^2 N p q}{(N - 1) d^2 + Z^2 p q}$$

where: n =sample size (85); N =maize grain production units (762); Z =confidence level (95%); d =absolute accuracy 0.1; and q =0.5 expected ratio.

The number of production units that constituted the population was taken from data of Mexico's National Institute of Statistics and Geography (INEGI, 2024b).

Surveys were administered through chain sampling. This technique, as it is based on reference networks (Arrogante, 2022), facilitated the participation of rainfed producers, who formed 78% of the sample, compared to 22% of producers with an irrigation regime.

The research was based on the analysis of profitability and competitiveness of four production systems of grain maize: i) Rainfed Native (Creole) grain maize; ii) Irrigated creole grain maize; iii) Rainfed Improved grain maize; and iv) Irrigated improved grain maize. The production systems Irrigated Creole grain maize (ii) and Rainfed improved grain maize (iii) were also evaluated environmentally; this meaning a decrease in the application of commercial agrochemicals in the cultivation activities of both systems in the municipality.

In order to determine the predominant activities and factors in the production of grain maize, information was collected by administering a specific questionnaire to maize producers of San José de Gracia (Aguascalientes, Mexico), and the national accounts for this crop, which provided the technical support for the construction of a matrix for policy analysis (MAP). This was created based on area planted, costs of tradable inputs, costs of factors of production, profits, volume of production, yields, taxes and subsidies.

After the MAP (Monke & Pearson, 1989) was integrated, we performed statistical analysis with SPSS v.27 ($\alpha=0.05$). Economic (Private) profitability was obtained by discounting private costs from private income. Social profitability was obtained by discounting social costs from incomes measured at social prices. Net transfers were obtained from the difference between private and social profitability. Private and social competitiveness were determined by the benefit/cost ratio (Table 1).

In accordance with the methodology proposed by Mexico's Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food, and the United Nations Food and Agriculture Organization (SAGARPA & FAO, 2008), social prices were estimated for the valuation of intermediate inputs. To this end, government sources were used, such as Mexico's National Foreign Trade Information Service (SNICE, 2022) and Mexico's Tax Revenue Administration Service (SAT, 2022), from which information was obtained regarding tariffs, taxes, inputs, subsidies and exchange rates.

The environmental assessment was developed through the MAP, in which the application of agrochemicals such as Sealant and Cypermethrin was reduced, as the use of production factors such as labor increased, by encouraging producers to do so. Therefore, in rainfed conditions, this analysis was called MAP environmental evaluation.

Table 1. Policy Analysis Matrix to evaluate production systems of grain maize in San Jose de Gracia, Aguascalientes, Mexico.

	Income	Costs		Profitability
		Tradable inputs	Factors of production	
Private prices	A	B	C	D
Social prices	E	F	G	H
Divergences	I	J	K	L
Private Profitability	D=A-B-C			
Social Profitability	H=E-F-G			
Transfers through the product	I=A-E			
Transfers through inputs	J=B-F			
Transfers through factors of production	K=C-G			
Net transfers	L=D-H			
	L=I-J-K			

Source: modified from Monke & Pearson (1989).

To assess the status of grain maize production, we used the summary coefficients proposed by Monke and Pearson (1989).

Nominal Protection Coefficients (NPCs) for commercial products and inputs; This indicator reflects the impact of fiscal policies on products and inputs, either through subsidies or taxes. Regarding the NPC for products, the value of $NPC > 1$ indicates that the market price is higher than the social price. On the other hand, a value of $NPC < 1$ for tradable inputs indicates that their market prices are below those that would prevail without the intervention of such policies.

$$NPC \text{ products} = \frac{\text{Income at private prices}}{\text{Income at social prices}}$$

$$NPC \text{ inputs} = \frac{\text{Cost of tradable inputs at market prices}}{\text{Cost of tradable inputs at social prices}}$$

Effective Protection Coefficients (EPCs) which allow for a comprehensive evaluation of the incentives granted to producers. The value of $EPC > 1$ reflects the presence of subsidies to producers, while a $EPC < 1$ value gives evidence regarding the application of taxes to producers.

$$EPC = \frac{\text{Income} - \text{Cost of tradable inputs at market prices}}{\text{Income} - \text{Cost of tradable inputs at social prices}}$$

Coefficient of the Cost of Factors of Production (CFP) that is a measure of efficiency and the presence of comparative advantages in agriculture production. The value of $CFP > 1$ indicates that the value of the factors used in the production process

exceeds the value added, when calculated at social prices. On the other hand, a $CFP < 1$ indicates that the producing area has comparative advantages in the crop analyzed.

$$CFP = \frac{\text{Cost of the workforce} + \text{Cost of capital}}{\text{Income} - \text{Cost of tradable inputs}}$$

RESULTS AND DISCUSSION

Profitability and private competitiveness of grain maize

Private profitability of grain maize expressed the economic situation of agricultural private producers (Table 2). This assessment considered the costs of tradable inputs, factors of production, and government inputs.

Under the irrigation regime, the costs averaged at 24 116.83 MXN \$ ha⁻¹; on the other hand, in rainfed regime costs reached an average of 9879.025 MXN \$ ha⁻¹. The cost analysis indicated that the farmers with the highest profitability and competitiveness were those who obtained higher grain maize yields, despite they paid high total costs.

At market prices, 64.9% of the grain maize produced in San José de Gracia was profitable; which was the corresponding to the systems under irrigation. The improved grain with irrigation system presented the highest yield with 7.2 tons (Megagrams) per hectare [Mg ha⁻¹]. Regarding competitiveness, the production system of Creole maize under irrigation reached 83.3%, which represents the greatest private competitiveness with an economic recovery of 78% for each \$ MXN (Mexican peso) invested.

At the opposite extreme of the range, the rainfed systems lacked profitability and competitiveness, registering an average yield of 0.525 Mg ha⁻¹. These systems presented economic losses when investing in agricultural production, estimating that, on average, 0.65 \$ MXN is lost for each Mexican peso invested. This can be attributed to irregular rainfall in the region, and to the lower use of inputs in this small-scale production.

The production system of irrigated Creole maize, evaluated from an environmental perspective, showed profitability and competitiveness, with a cost of compliance with the environmental standard of 2815 \$ MXN per hectare. In contrast, the improved (modified) grain maize in rainfed condition lacked profitability and competitiveness, recording an environmental cost of 3588.75 \$ MXN ha⁻¹. Overall, the environmental assessment showed no evidence of improvement in these indicators; moreover, an average reduction of 20% in profitability and 5.3% in competitiveness was observed, at market prices.

Table 2. Budget for grain maize production systems at private prices, and environmental evaluation in San Jose Gracia, Aguascalientes, Mexico.

Production systems for grain maize						
	i) Rainfed Creole	ii) Irrigated Creole	iii) Rainfed Improved	iv) Irrigated Improved	Irrigated Creole (Environmental)	Rainfed improved (Environmental)
Profitability MXN \$ ha ⁻¹	-7948.0	17 761.0	-4980.05	18 215.33	15 496.60	-5216.25
Competitiveness	0.32	1.78	0.38	1.71	1.70	0.35

Creole: native grain maize; Improved: modified grain maize variety.

In the national private production of grain maize, competitiveness reached 72.3% and profitability 86.9% (González & Alferes, 2010). With these values as reference, the municipal production we evaluated, presented levels of profitability and competitiveness lower than the national averages of Mexican grain maize production. These results suggest the need to improve management practices and strengthen policies and support to bring local indicators (at San Jose de Gracia, Aguascalientes) closer to domestic values (Mexico's national scale).

Social Profitability and Competitiveness of grain maize

Social profitability and social competitiveness of grain maize production were estimated under social efficiency prices, that is, without the influence of market distortions or public policies (Table 3).

This approach made it possible to contrast the results obtained with the actual situation of the producers; as well as, discussing to what extent Mexican Government interventions modified the economic viability of grain maize cultivation.

Compared to the private analysis, profitability and social competitiveness both registered reductions (37.43% and 12.08%). The production system of improved grain with irrigation showed the highest social profitability, followed by the Creole in irrigation system. In contrast, the production systems under rainfed condition did not present competitiveness or profitability. Social costs under rainfed conditions reached an average 10 158.17 MXN \$ ha⁻¹; on the other hand, irrigation costs averaged 26 377.03 MXN \$ ha⁻¹.

Production under irrigation regimes obtained average social benefits of 0.54 MXN ha⁻¹ (*i.e.* 54 cents for each Mexican peso invested per hectare). On the other hand, the systems under rainfed conditions lacked competitiveness, which translated into average economic losses of 70% MXN \$ ha⁻¹ [70 cents for each Mexican peso invested per hectare] (Table 3).

The Irrigated Creole production system, when it was environmentally evaluated at social prices, maintained profitability and competitiveness, even considering the cost of compliance with the standard for sustainability (2818 MXN ha⁻¹). This level of performance reflects greater resilience to environmental demands and a solid productive capacity to adapt. In contrast, the improved maize in rainfed condition presented unfavorable indicators, with a cost for compliance with the environmental standard of 791.65 MXN ha⁻¹. This is evidence of, even though the environmental cost was lower, low productivity prevented achieving conditions of profitability and competitiveness.

Table 3. Budget for production systems of grain maize at social prices, and environmental evaluation in San Jose Gracia, Aguascalientes, Mexico.

Production systems of grain maize						
	i) Rainfed Creole	ii) Irrigated Creole	iii) Rainfed improved	iv) Irrigated improved	Irrigated creole (environmental)	Rainfed improved (environmental)
Profitability MXN \$ ha ⁻¹	-9095.14	14 003.87	-5391.20	14 902.08	11 130.37	-6236.15
Competitiveness	0.23	1.54	0.36	1.55	1.43	0.31

Creole: native grain maize; Improved: modified grain maize variety.

This difference underscored the structural vulnerability of rainfed production systems and highlights the importance of strengthening technological water management in these schemes to prevent sustainability requirements from becoming an additional barrier to their economic viability.

Net Transfers: Grain Maize

The benefits transferred to grain maize production systems by Mexican Government market policies were assessed at private prices (Table 4). Creole grain under irrigation showed the highest transfer, with a benefit of 21.15%, followed by the improved grain in irrigation system (18.18%); then the rainfed Creole (14.43%), and the rainfed improved grain (8.25%). All of this shows the significant differences of the influence of government policies and the market on each production system.

Efficiency of grain maize production systems

Local grain maize producers obtained private support through the prices of the products. In contrast, the rainfed production system of improved grain maize did not show such economic aids, since its nominal protection coefficient for the commercial product was equal to 1 (Table 5).

The level of input prices for the irrigation and rainfed regimes were below the prices obtained in the absence of market distortions and Government policies. This indicated the presence of subsidies, reflected in the nominal protection coefficients for products and tradable inputs whose values were less than 1. Overall, the nominal protection coefficients for products and inputs showed that the production systems of grain maize, irrigated creole, rainfed improved, and irrigated improved, received economic supports, while the creole grain maize production system in rainfed condition presented levies.

Table 4. Net transfers for grain maize cultivation in San Jose de Gracia, Aguascalientes, Mexico.

	Rainfed Creole	Irrigated Creole	Rainfed improved grain	Irrigated improved grain
Private Profitability MXN \$ ha ⁻¹	-7948	17761	-4980.05	18215.33
Social Profitability MXN \$ ha ⁻¹	-9095.13	14003.86	-5391.20	14902.08
Divergences MXN \$ ha ⁻¹	1147.13	3757.13	411.15	3313.25

Table 5. Summary coefficients for the production systems of grain maize in San Jose de Gracia, Aguascalientes, Mexico.

Production system	Nominal Protection Coefficient		Effective Protection Coefficient	Costs of factors of production
	Product	Input		
Rainfed Creole maize	1.36	0.96	0.23	-5.00
Irrigated Creole maize	1.01	0.81	1.17	0.38
Rainfed Improved maize	1.00	0.81	1.51	7.52
Irrigated Improved maize	1.05	0.92	1.13	0.42

The combined effects of the policies on tradable goods markets indicated that only the rainfed creole maize producers faced levies, since the value of their EPCs turned out to be less than 1. The value of $EPC < 1$ can be attributed to the fact that the budget of the net supports was insufficient. This can be explained by the absence, or inadequacy of direct subsidies, as well as by market distortions or low-cost imports.

The grain maize production systems under the irrigation regime showed comparative advantages because they yielded coefficients of cost of the factors of production less than 1, around the levels reached at the national scale, 43.2% (González and Alferes, 2010). However, these indicators (profitability, competitiveness, and efficiency) are insufficient compared to other competing sectors of the labor market, such as the automotive industry or the local religious tourism, which are respectively 166% and 320% more profitable. In regard to the wages per agricultural worker, they obtained average benefits of 36.16 monthly minimum wages, while the automotive industry and religious tourism pay respectively, amounts of 47.68 and 77.13 minimum wages. According to Mexico's National Commission on Minimum Wages (CONASAMI, 2023), the minimum wage in 2024 was \$ 248.93 MXN, which indicates greater benefits and economic opportunities for workers in the manufacturing and tourism production chains (SALARYEPLORER, 2024).

CONCLUSIONS

At market and private prices, the irrigated improved grain production system presented the highest profitability, whereas the irrigated creole grain production system was superior for greater competitiveness. In the environmental analyses, both systems under irrigation regime maintained conditions of competitiveness and profitability. However, these indicators were lower compared to those obtained in the evaluation at private prices.

As a recommendation, it is suggested to implement policies and support that allow producers to internalize environmental costs without compromising profitability and competitiveness. This can strengthen the economic and environmental sustainability of grain maize production, as well as improve the resilience of irrigation systems while facing productive and climatic challenges.

REFERENCES

- Arrogante, Ó. (2022). Técnicas de muestreo y cálculo del tamaño muestral: Cómo y cuántos participantes debo seleccionar para mi investigación. *Enfermería intensiva*, 33(1), 44-47.
- Comisión Nacional de los Salarios Mínimos. (2023). Tabla de Salarios Mínimos Generales y Profesionales por Áreas Geográficas. <https://www.gob.mx/conasami/documentos/tabla-de-salarios-minimos-generales-y-profesionales-por-areas-geograficas>
- González, A., & Alferes, M. (2010). Competitividad y ventajas comparativas de la producción de maíz en México. *Revista mexicana de ciencias agrícolas*, 1(3), 381-396.
- De Grammont, H. C. (2010). La evolución de la producción agropecuaria en el campo mexicano: concentración productiva, pobreza y pluriactividad. *Andamios*, 7(13), 85-117.
- INEGI-Instituto Nacional de Estadística y Geografía. (2014). Resultados de la Encuesta Nacional de Ocupación y Empleo en el cuarto trimestre de 2013 para el estado de Aguascalientes. https://www.inegi.org.mx/contenidos/saladeprensa/boletines/2014/enoe_ie/enoe_ie2014_02_13.pdf
- INEGI-Instituto Nacional de Estadística y Geografía. (2024). Encuesta Nacional de Ocupación y Empleo (ENOE), Aguascalientes. https://www.inegi.org.mx/contenidos/saladeprensa/boletines/2025/enoe/enoe2025_02_Ags.pdf

- INEGI-Instituto Nacional de Estadística y Geografía. (2024a). Aspectos geográficos de Aguascalientes: Compendio 2023. https://www.inegi.org.mx/contenidos/productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/889463916680.pdf
- INEGI-Instituto Nacional de Estadística y Geografía. (2024b). Censo Agropecuario (CA) 2022. <https://www.inegi.org.mx/programas/ca/2022/#tabulados>
- López, J. (2017). Las políticas públicas del desarrollo industrial de Aguascalientes, México (1980-2014). *Revista de Economía*, 34(89), 42-77.
- Monke, E. A., & Pearson, S. R. (1989). The policy analysis matrix for agricultural development. A manual for practitioner [Matriz de análisis de políticas para el desarrollo agrícola. Manual para profesionales]. The Praga Corporation. Falls Church. Cepal.
- del Puerto Rodríguez, A. M., Suárez Tamayo, S., & Palacio Estrada, D. E. (2014). Efectos de los plaguicidas sobre el ambiente y la salud. *Revista Cubana de Higiene y Epidemiología*, 52(3), 372-387.
- SAGARPA & FAO-Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación., & Organización de las Naciones Unidas para la Alimentación y la Agricultura. (2008). Metodología de la medición de competitividad de sistemas producto. <https://www.agricultura.gob.mx/sites/default/files/sagarpa/document/2019/01/28/1608/01022019-metodologia-de-la-medicion-de-competividad-de-sistemas-producto.pdf>
- SALARYEPLORER. (2024). Automotive Average Salaries in Mexico 2024 [Salarios promedio en el sector automotriz en México 2024]. <http://www.salaryexplorer.com/salary-survey.php?loc=139&loctype=1&job=10&jobtype=1>
- SAT-Servicio de Administración Tributaria. (2022). Catálogos para la emisión de CFDI con complemento para Comercio Exterior versión 1.1. http://omawww.sat.gob.mx/tramitesyservicios/Paginas/catalogos_emision_cfdi_complemento_ce.htm
- SADER-Secretaría de Agricultura y Desarrollo Rural. (2023). Maíz, cultivo de México. <https://www.gob.mx/agricultura/articulos/maiz-cultivo-de-mexico#:~:text=Cultivo%20de%20ma%C3%ADz%20en%20M%C3%A9xico,los%2032%20estados%20del%20pa%C3%ADs>
- SIAP-Servicio de Información Agroalimentaria y Pesquera. (2025). Anuario Estadístico de la Producción Agrícola. https://nube.agricultura.gob.mx/cierre_agricola/
- SNICE-Servicio Nacional de Información de Comercio Exterior. (2022). SIAVI Data. <http://187.217.44.135/eid/web/preclasificadorexterno>
- Vargas, A., & Rodríguez, I. (2021). Aguascalientes, 20 años en el camino de la gestión del desarrollo turístico. In: *El desarrollo turístico en México* (1ª ed., pp. 105 – 169). https://simehbucket.s3.amazonaws.com/miscfiles/el-desarrollo-turistico-en-mx-electronico_f55kmeh8.pdf#page=105

GIS and modeling to determine key areas for conserving the genetic diversity of cotton (*Gossypium* spp.) in Mexico

Caballero-García, Marco A.¹; Santoyo-Cortés, Vinicio H.^{2*}; López-Herrera, Agustín J.³; Ríos-Santos, E.¹; Rebollar-Ávila, C.¹; Ramírez-Galindo, J.¹

¹ Servicio Nacional de Inspección y Certificación de Semillas. Coyoacán, Ciudad de México, México. C. P. 04100.

² Universidad Autónoma Chapingo, Centro de Investigaciones Económicas, Sociales y Tecnológicas de la Agroindustria y la Agricultura Mundial- CIESTAAM, carretera federal México- Texcoco km 38.5, Texcoco, Estado de México, México. C. P. 56230.

³ Universidad Autónoma Chapingo, carretera federal México- Texcoco km 38.5, Texcoco, Estado de México, México. C. P. 56230.

* Correspondence: hsantoyo@ciestaam.edu.mx

ABSTRACT

Objective: to determine the key genetic pool areas that harbor populations of wild relatives of cotton in Mexico, through GIS and modeling.

Design/ Methodology/ Approach: a database with 2594 records of collections of the genus *Gossypium* was used, the data were obtained since 1933 up to 2024. A map was created to visualize the geographical distribution of the species and another for genetic diversity where the Shannon diversity index (SDI) was applied.

Results: an 80% of the records of wild relatives of cotton are conformed by *Gossypium hirsutum* (58.8%), *G. aridum* (14.1%) and *G. davidsonii* (6.7%), confirming that Mexico is the center of diversity for *G. hirsutum*. Five key areas with very high genetic diversity were identified in the states of Oaxaca and Michoacán.

Limitations/Implications of the study: the target of this study were only wild populations, it did not evaluate GMO's genetic cross-contamination. However, the study emphasizes the importance and role of cotton genetic pools that are still preserved in natural populations. This may lead decision making towards the need for conservation areas in public policies.

Findings/Conclusions: five key areas with very high genetic diversity were identified in the states of Oaxaca and Michoacán. In the states of Guerrero, Baja California Sur and Sonora, areas with a high concentration of some *Gossypium* species were identified, and therefore could be considered key areas for the conservation of *Gossypium* genetic diversity.

Keywords: conservation, genetic pool, spatial distribution, *Gossypium*, Shannon Diversity Index.

Citation: Caballero-García, M. A., Santoyo-Cortés, H. V., López-Herrera, A. J., Ríos-Santos, E., Rebollar-Ávila, C., & Ramírez-Galindo, J. (2026). GIS and modeling to determine key areas for conserving the genetic diversity of cotton (*Gossypium* spp.) in Mexico. *Agro Productividad*. <https://doi.org/10.32854/db9ew164>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: September 6, 2025.

Accepted: January 5, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 183-193.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

At the beginning of the 16th century, Mexico was inhabited by cultures with diverse political, social, agricultural, and economic systems. The development of these cultures was favored by the varied natural conditions that offered a wide diversity of native plants, which allowed for their use and domestication. Such as maize, beans, chili peppers, squash,

cotton, amaranth, and cacao, among others, which have made significant contributions to global agriculture and food security (SNICS, 2020).

There are about 50 known species of cotton (*Gossypium* spp.). The centers of greatest species richness of the genus *Gossypium* are found in Central and South America, 18 species; Australia 17 species, Northeast Africa and Southwest Arabia, 14 species. In Mexico, according to the Germplasm Resources Information Network (GRIN), the USDA's Agricultural Research Service reported 15 out of the 18 existing cotton species in Central and South America, distributed across 87% of the US national territory (USDA-ARS, 2024). The highest concentrations of wild cotton relatives are located in the southeastern region of the country (Coppens d'Eeckenbrugge & Jean-Marc, 2014).

The two most cultivated species are *G. hirsutum* and *G. barbadense*. For *G. hirsutum*, the center of origin and greatest diversity is recorded as located in Southern Mexico and Central America. Its possible center of domestication is located in Southeastern Mexico, in the Yucatán Peninsula. And the species *G. barbadense* comes from Peru.

In Mexico, the first region where cotton is believed to have been cultivated was Veracruz in the 16th century. From 1860 onward, interest in its cultivation increased considerably in various regions of the country (CIBIOGEM, 2014). The Comarca Lagunera (a region encompassing parts of Coahuila and Durango), Chihuahua, Sinaloa, Sonora, Baja California, and Tamaulipas have been the main producing states. Records also exist of cotton cultivation in Campeche, Colima, Chiapas, Michoacán, Nuevo León, San Luis Potosí, Veracruz, and Yucatán (INEGI, 1994).

Between 1950 and 1969, approximately one million hectares (ha) were planted (INEGI, 1994). From 1970 onward, the planted area began to decline, and by the 1980s only 300 000 ha were cultivated, a figure that dropped to 82 000 ha in 2000 (INEGI, 1994). This decline and gradual abandonment of cotton crop was due to factors such as the uncompetitive international price of this fiber, caused by a rapid substitution with synthetic fibers. Also, by the emergence of pests, which led to the use of high doses of agrochemicals that increased production costs (Reyes *et al.*, 2010).

In 1996, with the planting of 896 hectares, Mexico began cotton production using genetically modified (GM) seeds of the species *G. hirsutum*, resistant to pests and tolerant to diseases, to reduce production costs (SNICS, 2020). By 2024, cotton production had recovered, approximately 240 000 hectares were planted, 96% of which used GM seeds (SIAP, 2024). Genetically modified cotton is not cultivated in Oaxaca, Chiapas, and Yucatán, rather wild *G. hirsutum* populations still exist.

One of the risks of genetically modified crops is that the genes can be introduced into the diversity of wild plants and conventional crops grown in a region, potentially leading to genetic contamination (Pons, 2021). Ulloa *et al.* (2006) observed that the expansion of GMOs cultivation has increased the risk of loss of native varieties, as it can cause genetic erosion. For this reason, it is important to consider countries that are centers of origin and genetic diversity, such as Mexico (Pérez *et al.*, 2016).

Regarding this aspect, the Mexican Biosafety Law for Genetically Modified Organisms (LBOGM) establishes criteria for determining the centers of origin and genetic diversity of crops. According to this Law, a center of origin is defined as a geographic area where

the domestication process of a given species took place. Whereas, a center of genetic diversity is defined as a geographic area where considerable morphological and genetic diversity exist for certain species. This site is characterized by harboring populations of wild relatives that together constitute a genetic pool. Due to the importance of identifying key genetic pool areas to prevent the establishment of transgenic commercial crops in their vicinity, this research was designed to provide information for defining public policies for the sustainable production and use of cotton, as well as for the conservation of cotton genetic diversity in Mexico. The objective was to determine the key genetic pool areas that harbor populations of wild relatives of cotton in Mexico, through the use of GIS and modeling.

MATERIALS AND METHODS

Database integration

A database was compiled with 2594 records of collections of the genus *Gossypium*. The data started in 1933 and were collected up to 2024, of which 801 records came from the Conservation Centers Network, coordinated by the Subcommittee on Agricultural Genetic Resources of Mexico's Secretariat of Agriculture (by email communication); 946 records from the National Biodiversity Information System of Mexico's National Commission for the Knowledge and Use of Biodiversity, under the Secretariat of Environment and Natural Resources (CONABIO, 2024); and 847 records proceed from the WN003 Project of Mexico's Conservation Program of Wild Populations of the genus *Gossypium* in Mexico, under the National Commission for the Knowledge and Use of Biodiversity (CONABIO, 2022).

The database included variables such as biological complex, biological status, state, municipality, and origin (locality), in addition to identification data and location coordinates. Duplicated records and those lacking a collection number or code, collection year, or collector identification were eliminated. Likewise, some errors when records were geographically referred, such as those located in inland water bodies or outside municipal boundaries, were identified and corrected. To ensure data accuracy, a detailed verification was performed at municipal scale using the Mexico's National Geo-Statistical Framework, integrated to Mexico's National Geo-Statistical Information System, created by Mexico's National Institute of Statistics and Geography (INEGI, 2023). Finally, those records classified as 'non-wild', 'feral', 'cultivated', or 'semi-domesticated' were excluded. The final database consisted exclusively of wild individuals and comprised a total of 1385 records corresponding to 13 species (Table 1).

In order to systematize the information, the records were classified according to state of origin and species. Then, a temporal classification of the species (by year of record collection) was performed. For this, Jenks's natural break optimization method (Jenks, 1967) was used. This statistical algorithm objectively identifies the optimal breakpoints in the data, resulting in five time intervals that maximize the variance between groups and minimize the variance within each group. This ensures that the resulting interval groups are statistically distinct, internally consistent, and significant.

Table 1. Number of records of wild relatives of cotton (*Gossypium* spp.) in data obtained since 1933 to 2024.

Number	Species	Number of records	Value in database (%)
1	<i>G. hirsutum</i>	815	58.8
2	<i>G. aridum</i>	195	14.1
3	<i>G. davidsonii</i>	93	6.7
4	<i>G. harknessii</i>	74	5.3
5	<i>G. thurberi</i>	49	3.5
6	<i>G. gossypoides</i>	45	3.2
7	<i>G. lobatum</i>	33	2.4
8	<i>G. laxum</i>	29	2.1
9	<i>G. armourianum</i>	14	1
10	<i>G. trilobum</i>	14	1
11	<i>G. schwendimanii</i>	11	0.8
12	<i>G. barbadense</i>	9	0.6
13	<i>G. turneri</i>	4	0.3
	Total	1385	100

Areas with populations of wild relatives

To visualize the geographic distribution of the 13 species of wild relatives of cotton, the 1385 records from the final database were used, and a map was created using the open-source GIS software QGIS (2024). A diversity map was then generated, calculating the Shannon Diversity Index (SDI) with a spatial resolution of $33 \times 33 \text{ km}^2$, using DIVA-GIS, another open-source module (Hijmans, 2024). This index is widely used to quantify species biodiversity (Pla, 2006). A value trending towards 1 indicates very high diversity, while a value trending towards 0 indicates low diversity, since it considers both the number of species present (richness), and their relative abundance (evenness). This map shows how species diversity and richness are distributed in a given area.

RESULTS AND DISCUSSION

Table 2 and Table 3 show the reclassification of records based on the state of origin, species, and year of the record. Thirteen species of wild relatives of cotton were identified (Table 2), with a significant degree of updating, as 50% of these were recruited between 2009 and 2024 (Table 3). This number and type of species identified coincides with Pérez *et al.* (2016), whose study considered cotton records collected since 1978 to 2006.

However, these results do not include the presence of two species, *Gossypium raimondii* with distribution records in the State of Mexico, and *G. lanceolatum* with distribution records in Michoacán and Nayarit, which are reported, as part of the 15 cotton species distributed in Mexico, by the US Germplasm Resources Information Network–GRIN (Campbell *et al.*, 2010; USDA-ARS, 2024).

Results showed that 80% of the records of cotton wild relatives are concentrated in three species *G. hirsutum* 58.8%; *G. aridum* 14.3% and *G. davidsonii* 6.7%. This reflects the

Table 2. Classification of records according to the Mexican state of origin and the species of the genus *Gossypium*.

Mexican state	Species													Total
	<i>G. aridum</i>	<i>G. armourianum</i>	<i>G. barbadense</i>	<i>G. davidsonii</i>	<i>G. gossypoides</i>	<i>G. harknessii</i>	<i>G. hirsutum</i>	<i>G. laxum</i>	<i>G. lobatum</i>	<i>G. schwendimanii</i>	<i>G. thurberi</i>	<i>G. trilobum</i>	<i>G. turneri</i>	
Aguascalientes							1							1
Baja California Sur		14		79		73	4							170
Campeche							16							16
Chiapas			9				31							40
Chihuahua							1				3			4
Colima	21						8							29
Durango	1													1
Guerrero	17						33	29	1	2		1		83
Jalisco	18						8							26
México							2							2
Michoacán	10						27		32	9		12		90
Morelos							5					1		6
Nayarit	13						5							18
Oaxaca	67				44		178							289
Puebla	9				1		8							18
Querétaro							1							1
Quintana Roo							12							12
San Luis Potosí							3							3
Sinaloa	30						7							37
Sonora				14		1					46		4	65
Tabasco							2							2
Tamaulipas							10							10
Veracruz	9						17							26
Yucatán							436							436
Total	195	14	9	93	45	74	815	29	33	11	49	14	4	1385

relevance of *G. hirsutum* in Mexico as the species which is source of diversity and genetic richness. It coincides with what was reported by Wegier *et al.* (2012) who indicated that Mexico is the center of diversity for *G. hirsutum*. Furthermore, the wide distribution of this species as a wild species within Mexican territory was demonstrated.

Yucatán and Oaxaca are the states with the highest number of records of *G. hirsutum*, 436 and 178 (Table 2), which coincides with Pérez & Ruiz (2010) who reported that the center of origin and greatest genetic diversity of *G. hirsutum* is located in the south of the country.

Table 3. Classification by collecting period of the different species of *Gossypium* spp.

Species	Periods (years)					Total
	1933-1955	1956-1975	1976-1993	1994-2008	2009-2024	
<i>G. aridum</i>	4	20	60	94	17	195
<i>G. armourianum</i>	4	4	1	1	4	14
<i>G. barbadense</i>				9		9
<i>G. davidsonii</i>	8	28	21	27	9	93
<i>G. gossypoides</i>		5	15	7	18	45
<i>G. harknessii</i>	7	23	22	13	9	74
<i>G. hirsutum</i>	84	9	30	81	611	815
<i>G. laxum</i>		7	7	12	3	29
<i>G. lobatum</i>	2	1	4	21	5	33
<i>G. schwendimanii</i>			1	9	1	11
<i>G. thurberi</i>	9	2	14	13	11	49
<i>G. trilobum</i>	3	5	4		2	14
<i>G. turneri</i>		1	3			4
Total	121	105	182	287	690	1385

Regarding the geographical distribution of current records of wild relatives of cotton, their presence is evident in 24 Mexican states, from the Northwest (Sonora, Baja California Sur and Sinaloa) to the Southeast in the Yucatan Peninsula and Quintana Roo (Figure 1). These results contrast with those of Pérez *et al.* (2016), who determined the presence of native cotton species in 27 states. The difference is possibly due to the aforementioned study included individuals classified as non-wild, that is, cultivated.

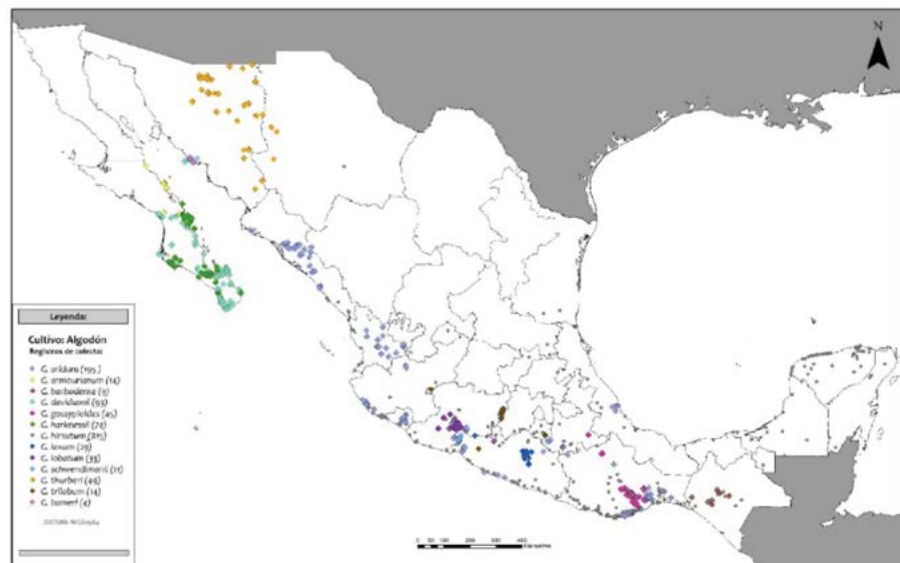


Figure 1. Geographic distribution of wild relatives of cotton (*Gossypium* spp.) in Mexico. Prepared by the authors using QGIS (2024).

These records highlight that 65% of wild relatives, and therefore the genetic richness, are concentrated in Yucatán (31%) and Oaxaca (21%). This coincides with Cronn *et al.* (2003) and Álvarez *et al.* (2005), who located the center of origin of *Gossypium diploides* in Oaxaca, while the origin of *Gossypium tetraploides* was located ‘somewhere in Mesoamerica’, which includes Yucatan.

In the remaining 22 Mexican states, several species have very restricted distributions in terms of both number and geographic range. Some are represented by only a single species record, but are found in various coastal regions of Baja California Sur, the Pacific Ocean, the Gulf of Mexico, and the Yucatán Peninsula. In other words, the genus *Gossypium* is found in areas with conditions ranging from arid to humid and semi-warm to warm, associated with geological and edaphic diversity, as well as different vegetation and habitat types. Five key areas of very high species diversity were identified (within $33 \times 33 \text{ km}^2$ geographic cells) with a Shannon diversity index between 0.76 and 1 (Figure 2).

In these red areas, at least three species are present, *Gossypium aridum*, *G. hirsutum*, and *G. gossypioides*. Two of these areas are located in the central and northeastern regions of the state of Michoacán; five species are distributed within them (*Gossypium lobatum*, *G. hirsutum*, *G. trilobum*, *G. aridum* and *G. schwendimanii*). In a first area, the species *G. aridum*, *G. hirsutum* and *G. lobatum* are located; in a second area we found the species *G. aridum*, *G. lobatum* and *G. schwendimanii*. The remaining three areas are located in the Southeast of Oaxaca and all areas share the distribution of the species *G. aridum*, *G. gossypioides* and *G. hirsutum* (Table 4).

In addition, 24 areas with high diversity (IDS between 0.57 and 0.75) were identified and are depicted in orange in Figure 2. Six areas were recorded in the state of Baja

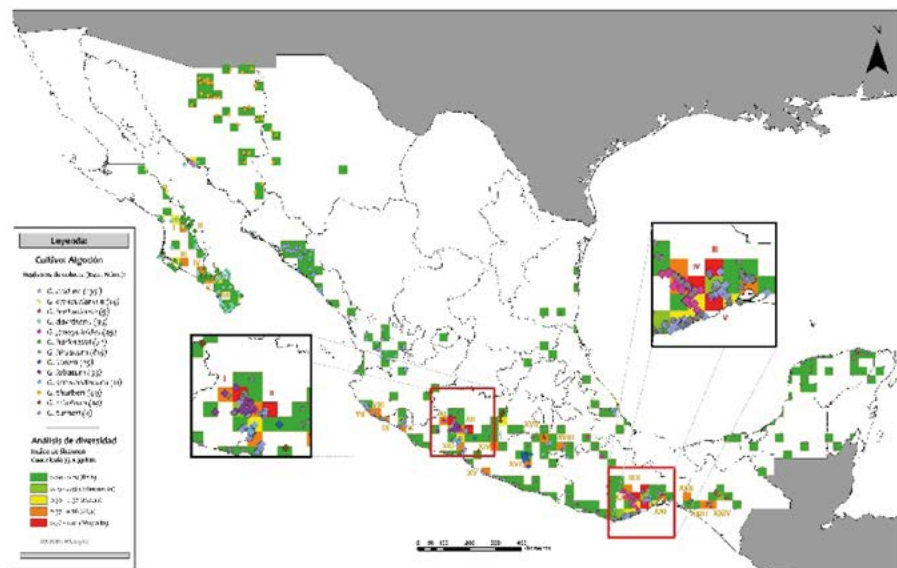


Figure 2. Key areas of very high richness and diversity of cotton (*Gossypium* spp.) wild relatives in Mexico. Prepared by the authors using DIVA-GIS.

Table 4. Key areas of very high diversity based on the Shannon diversity index (SDI 0.764-1.00).

Key Area	State	Municipalities	Species
I	Michoacán	Parácuaro, Múgica y Gabriel Zamora	<i>G. hirsutum</i> , <i>G. lobatum</i> and <i>G. aridum</i>
II	Michoacán	La Huacana, Churumuco y Turicato	<i>G. schwendimanii</i> , <i>G. lobatum</i> and <i>G. aridum</i>
III	Oaxaca	Santiago Ixcuintepec, Santo Domingo Tehuantepec, Santiago Lachiguiri, Nejapa de Madero, Guevea de Humboldt y Santa María Guienagati	<i>G. hirsutum</i> , <i>G. gossypoides</i> and <i>G. aridum</i>
IV	Oaxaca	Santa Ana Tavela, San Juan Lajarcia, San Carlos Yautepec, San Bartolo Yautepec, Santa María Ecatepec, Magdalena Tequisistlán, Santa María Jalapa del Márques y Santa María Totolapilla	<i>G. hirsutum</i> , <i>G. gossypoides</i> and <i>G. aridum</i>
V	Oaxaca	Magdalena Tequisistlán, San Miguel Tenango, Santo Domingo Tehuantepec y San Pedro Huamelula	<i>G. hirsutum</i> , <i>G. gossypoides</i> and <i>G. aridum</i>

California Sur, where cotton species converge, *Gossypium armourianum*, *G. harknessii* and *G. davidsonii*. Also, four areas in Guerrero with *G. aridum*, *G. hirsutum*, *G. laxum*, *G. lobatum* and *G. schwendimanii*; three areas in Oaxaca with *G. aridum*, *G. gossypoides* and *G. hirsutum*; and three areas in Chiapas with *G. barbadense* and *G. hirsutum* (Table 5).

Areas with medium diversity (SDI 0.38-0.57) were also delimited with their species, and were identified with yellow color (Figure 2). These are located in Baja California Sur (*Gossypium armourianum*, *G. hirsutum*, *G. davidsonii* and *G. harknessii*); Sonora (*G. davidsonii*, *G. harknessii* and *G. turneri*); Michoacán (*G. aridum* and *G. schwendimanii*); State of Mexico (*G. hirsutum* and *G. trilobum*); Oaxaca (*G. aridum*, *G. gossypoides* and *G. hirsutum*) and Veracruz (*G. hirsutum* and *G. aridum*). Those areas with intermediate diversity (SDI 0.19-0.38; lime green in Figure 2) are located in Colima (*G. aridum* and *G. hirsutum*); Michoacán (*G. aridum*, *G. hirsutum* and *G. lobatum*); Oaxaca (*G. aridum* and *G. hirsutum*) and Chiapas (*G. barbadense* and *G. hirsutum*).

Areas with low diversity (SDI 0-0.19, dark green in Figure 2) are characterized by the presence of a single species. These low diversity areas are more frequent and dispersed, and are located in northern Sonora (*G. thurberi*), central Sinaloa (*G. aridum*), and a large area in Yucatán (*G. hirsutum*). The latter accounts for 32% of all *Gossypium* records.

In turn, Michoacán, Guerrero, Baja California Sur, Oaxaca, Jalisco, Colima, State of Mexico, Morelos, Puebla and Chiapas are highlighted because these states have areas with greater diversity. This is, considering both the number of species present (richness) and their relative abundance (evenness). In these places, genetically modified cotton could represent a risk of genetic contamination.

Table 5. Key areas of high diversity according to Shannon index (SDI 0.573-0.764).

Key Area	State	Municipalities	Species
I and II	Baja California Sur	Loreto	<i>G. davidsonii</i> and <i>G. harknessii</i>
III	Baja California Sur	Comondú and La Paz	<i>G. davidsonii</i> and <i>G. harknessii</i>
IV	Baja California Sur	La Paz	<i>G. davidsonii</i> and <i>G. harknessii</i>
V	Baja California Sur	La Paz	<i>G. davidsonii</i> , <i>G. harknessii</i> and <i>G. armourianum</i>
VI	Baja California Sur	La Paz	<i>G. davidsonii</i> , <i>G. harknessii</i> and <i>G. hirsutum</i>
VII	Jalisco	La Huerta	<i>G. hirsutum</i> and <i>G. aridum</i>
VIII	Jalisco	La Huerta and Cihuatlán	<i>G. hirsutum</i> and <i>G. aridum</i>
IX	Colima	Cihuatlán and Manzanillo	<i>G. hirsutum</i> and <i>G. aridum</i>
X	Colima	Armería and Tecomán	<i>G. hirsutum</i> and <i>G. aridum</i>
XI	Michoacán	Buenavista, Tancítaro and Apatcingán	<i>G. hirsutum</i> and <i>G. lobatum</i>
XII	Michoacán	La Huacana and Churumuco	<i>G. hirsutum</i> , <i>G. lobatum</i> and <i>G. aridum</i>
XIII	Guerrero	La Unión Isidoro Montes de Oca and Coahuayutla de José María Izazaga	<i>G. schwendimanii</i> and <i>G. aridum</i>
XIV	Guerrero	Coyuca de Catalán, Pungarabato, Tlapehuala and Ajuchitlán del Progreso	<i>G. hirsutum</i> and <i>G. lobatum</i>
XV	Guerrero	Petatlán and Técpan de Galeana	<i>G. hirsutum</i> and <i>G. aridum</i>
XVI	Guerrero	Leonardo Bravo, Eduardo Neri, Tixtla de Guerrero and Chilpancingo de los Bravo	<i>G. hirsutum</i> , <i>G. aridum</i> and <i>G. laxum</i>
XVII	Morelos	Tepalcingo, Tlalquitenango, Teotlalco, Ayala, Tlaltizapan de Zapata and Jolalpan	<i>G. hirsutum</i> and <i>G. trilobum</i>
XVIII	Puebla	Chiautla, Tehuiztingo, Izucar de Matamoros, Chila de la Sal, Axutla, Tecomatlán, Piaxtla, Ahuehuetitla, Chinantla	<i>G. hirsutum</i> and <i>G. aridum</i>
XIX	Oaxaca	San Pedro Quiatoni, San Juan Juquila Mixes, Santa María Tepantlali, Santo Domingo Tepuxtepec, San Juan del Rio, San Lorenzo Albarradas, Tlacolula de Matamoros and San Pedro Totolapám	<i>G. hirsutum</i> and <i>G. gossypoides</i>
XX	Oaxaca	San Pedro Totolapám, San Carlos Yautepec, Santa María Quiegolani, San Bartolo Yautepec, San Carlos Yautepec, San Juan Lajarcia, Santa Ana Tavela and Nejapa de Madero	<i>G. hirsutum</i> and <i>G. gossypoides</i>
XXI	Oaxaca	Asunción Ixtaltepec, El Espinal, Juchitán de Zaragoza, Santa María Xadani, Unión Hidalgo, San Dionisio del Mar, Santiago Niltepec, Santo Domingo Ingenio and San Miguel Chimalapa	<i>G. hirsutum</i> and <i>G. aridum</i>
XII	Chiapas	Cintalapa de Figueroa, San Pedro Tapanatepec, Arriaga and Jiquipilas	<i>G. barbadense</i> and <i>G. hirsutum</i>
XXIII	Chiapas	Villaflores and Villa de Corzo	<i>G. barbadense</i> and <i>G. hirsutum</i>
XXIV	Chiapas	Villaflores, Villa de Corzo and El Parral	<i>G. barbadense</i> and <i>G. hirsutum</i>

CONCLUSIONS

Of the cotton species recorded, three dominate the distribution; *Gossypium hirsutum* (58.8%), *G. aridum* (14.3%) and *G. davidsonii* (6.7%), which emphasizes that Mexico is the center of diversity for *G. hirsutum*, this also coincides with previous research.

Five key areas with very high genetic diversity in species of *Gossypium* were identified, as well as 24 areas with high genetic diversity. It is recommended that these areas be designated as areas where genetically modified cotton cultivation should not be permitted, as this poses a risk of genetic contamination to native species and their conservation.

The greatest genetic diversity of *Gossypium* is concentrated in Michoacán, Guerrero, and Oaxaca, with a significant presence in Baja California Sur and Sonora. This strengthens the theory that Southern Mexico is a center of origin and diversity for these species. It should be emphasized that both, areas with the greatest genetic richness and those with a high concentration of a single species are key to conserving the genetic biodiversity of the genus *Gossypium*.

REFERENCES

- Álvarez I., R. Cronn & J. F. Wendel (2005) Phylogeny of the new world diploid cottons (*Gossypium* L., Malvaceae) based on sequences of three low-copy nuclear genes. *Plant systematics and evolution* 252:199-214. <https://doi.org/10.1007/s00606-004-0294-0>
- Campbell B. T., S. Saha, R. Percy, J. Frelichowski, J. N. Jenkins, W. Park, C. D. Mayee, V. Gotmare, D. Dessauw, M. Giband, X. Du, Y. Jia, G. Constable, S. Dillon, I. Y. Abdurakhmonov, A. Abdurakarimov, S. M. Rizaeva, A. Abdullaev, P. A. V. Barroso, J. G. Pádua, L. V. Hoffmann & L. Podolnaya (2010) Status of global cotton germplasm resources. *Crop Science* 50(4):1161-1179. <https://doi.org/10.2135/cropsci2009.09.0551>
- CIBIOGEM, Comisión Intersecretarial de Bioseguridad de los Organismos Genéticamente Modificados (2014) Algodón. <https://www.conacyt.gob.mx/cibiogem/index.php/algodon> (January 2025).
- CONABIO, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (2022) *Gossypium hirsutum*. Distribución puntual del algodón silvestre en México, escala: 1:250000. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. Registros silvestres de la especie *Gossypium hirsutum* en México. Ciudad de México, México. <http://geoportal.conabio.gob.mx/metadatos/doc/html/goshirdcgw.html> (January 2025).
- CONABIO, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (2024) Sistema Nacional de Información sobre Biodiversidad. Registros de ejemplares. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. Ciudad de México, México. <https://www.snib.mx/ejemplares/download/> (January 2025).
- Coppens d'Eeckenbrugge G., & L. Jean-Marc (2014) Distribution and differentiation of wild, feral, and cultivated populations of perennial upland cotton (*Gossypium hirsutum* L.) in Mesoamerica and the Caribbean. *PLoS ONE* 9(9):1-19. <https://doi.org/10.1371/journal.pone.0107458>
- Cronn R., R. L. Small, T. Haselkorn & J. F. Wendel (2003) Cryptic repeated genomic recombination during speciation in *Gossypium gossypoides*. *Evolution* 57(11):2475-2489. <https://doi.org/10.1111/j.0014-3820.2003.tb01493.x>
- Hijmans, R. J. (2024) A geographic information system for the analysis of biodiversity data (Version 7.5.0). Retrieved: <https://diva-gis.org/>
- INEGI, Instituto Nacional de Estadística, Geografía e Informática (1994) Estadísticas Históricas de México. Tomo II. Tercera edición. México. 468 p.
- INEGI, Instituto Nacional de Estadística y Geografía (2023). Marco Geoestadístico Nacional. Sistema Nacional de Información Estadística y Geográfica. <https://www.inegi.org.mx/programas/mg/> (January 2025).
- Jenks G. F. (1967) The data model concept in statistical mapping. *International Yearbook of Cartography* 7:186-190.
- Pérez M. C. & J. A. C. Ruiz (2010) Diagnóstico de la situación actual de los recursos genéticos del algodón en México. Resumen. In: V Reunión Nacional de Investigación Agrícola. 204 p.

- Pérez M. C., Ma. del R. Tovar G., Q. Obispo G., F. de J. Legorreta P. & J. A. Ruiz C. (2016) Recursos genéticos del algodón en México: Conservación *ex situ*, *in situ* y su utilización. *Revista Mexicana de Ciencias Agrícolas* 7(1):5-16.
- Pla L. (2006) Biodiversidad: Inferencia basada en el índice de Shannon y la riqueza. *Interciencia* 31(8): 583-590.
- Pons G. J. M. (2021) Los efectos del cultivo del algodón transgénico. *Educación Ambiental*. <https://www.gob.mx/semarnat/educacionambiental/es/articulos/los-efectos-del-cultivo-del-algodon-transgenico?idiom=es> (January 2025).
- QGIS (2024) Sistema de información geográfica QGIS. Proyecto de la Fundación Geoespacial de código abierto. <http://qgis.org>
- Reyes G., A. Chaparro-Giraldo, K. Ávila (2010) Efecto ambiental de agroquímicos y maquinaria agrícola en cultivos transgénicos y convencionales de algodón. *Revista Colombiana de Biotecnología* 12(2):151-162.
- SIAP, Servicio de Información Agroalimentaria y Pesquera (2024) Panorama Agroalimentario 2024. <https://www.gob.mx/siap/acciones-y-programas/panorama-agroalimentario-258035> (January 2025).
- SNICS, Servicio Nacional de Inspección y Certificación de Semillas (2020) Informe Nacional Sobre el Estado de los Recursos Fitogenéticos para la Alimentación y la Agricultura. Servicio Nacional de Inspección y Certificación de Semillas. México. 319 p.
- SNICS, Servicio Nacional de Inspección y Certificación de Semillas (2020) Programa de abasto de semilla de algodón. 71 p.
- Ulloa M., J. M. Stewart, E. A. García-C, S. Godoy-A., A. Gaytán-M., & N. S. Acosta (2006) Cotton genetic resources in the western states of México: *In situ* conservation status and germplasm collection for ex situ preservation. *Genetic Resources and Crop Evolution* 53:653-668. <https://doi.org/10.1007/s10722-004-2988-0>
- USDA-ARS, United States Department of Agriculture–Agricultural Research Service. (2024) Germplasm Resources Information Network (USDA-ARS-GRIN). <https://www.ars-grin.gov/>
- Wegier B. A. L., V. Alavez G., L. O. Jardón B., L. Moyers, D. Ortega del V. & D. Piñero (2012) Análisis para la determinación de los centros de origen y diversidad de las especies mexicanas del género *Gossypium*. Instituto de Ecología, UNAM. 24 p.

Sustainable alternative: A forage prickly pear cactus (*Opuntia ficus-indica* L. Mill.) production system for cattle fattening

Torres-Madrid, Diana M.¹; Uranga-Valencia, Luisa P.^{1*}; Terrazas-Gómez, Marina I.¹; Pérez-Álvarez, Sandra¹; Narváez-Flores, Raúl¹

¹ Facultad de Ciencias Agrícolas y Forestales. Km. 2.5 carretera Rosales, poniente, Delicias, Chihuahua, México. C. P. 33000.

* Correspondence: luranga@uach.mx

ABSTRACT

Objective: In arid regions such as south-central Chihuahua, Mexico, water scarcity and soil degradation affect agricultural sustainability. The forage cactus (*Opuntia ficus-indica*) has proven to be a viable option under these conditions due to its resilience and low water requirements. This study established a cactus production system in a 500 m² experimental plot to evaluate soil improvement, water-use efficiency, and economic investment associated with the planting method.

Design/Methodology/Approach: Comparative soil analyses were conducted before and after planting, improved irrigation practices were implemented, and the Baca Urbina methodology was applied for the economic analysis.

Results: Organic matter increased from 0.5% to 2.36%, and essential nutrients such as nitrates, phosphorus, and potassium also improved, while calcium carbonate levels decreased. Drip irrigation supplied 1.5 L over 4.5 h per month, with an initial investment of \$50,000 MXN. The economic analysis yielded a net present value (NPV) of \$42,075.89 MXN, an internal rate of return (IRR) of 39.48%, and a cost–benefit ratio (CBR) of 2.03.

Findings/Conclusions: The production system reduced potential cattle feed costs and improved water-use efficiency, demonstrating that forage cactus is profitable and sustainable for small producers in arid and semi-arid areas. Seasonal variability and plot size could influence the results, so it is recommended to expand the trials to different scales and climatic conditions.

Keywords: forage cactus, soil restoration, soil improvement, sustainable agriculture, arid regions.

Citation: Torres-Madrid, D. M., Uranga-Valencia, L. P., Terrazas-Gómez, M. I., Pérez-Álvarez, S., & Narváez-Flores, R. (2026). Sustainable alternative: A forage prickly pear cactus (*Opuntia ficus-indica* L. Mill.) production system for cattle fattening. *Agro Productividad*. <https://doi.org/10.32854/t5gn5638>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: September 28, 2025.

Accepted: January 13, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 195-204.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.

INTRODUCTION

In northern Mexico, cattle fattening systems face significant challenges due to the limited availability and high cost of forage resources, conditions that are further exacerbated by recurrent drought and soil degradation (Gutiérrez-Luna *et al.*, 2012). These factors have forced producers, particularly small- and medium-scale farmers, to adopt intensive production systems to compensate for pasture deficiencies; however, such systems require increasing investments that hinder their economic viability (Lara-Pulido *et al.*, 2020).



Overgrazing, resulting from excessive stocking rates, intensifies forage scarcity and compromises animal nutrition and welfare (Flores-Ortiz & Reveles-Hernández, 2010). Consequently, traditional forages such as alfalfa, sorghum, wheat, and maize are commonly used; nevertheless, their high costs have driven the search for affordable alternatives adapted to local conditions, among which forage cactus stands out (SADER, 2018). This forage cactus (*Opuntia ficus-indica*) is widely distributed across the country's semi-arid and arid regions, where climatic and edaphic constraints limit the development of conventional crops (López-González, 2008).

This cactus has transcended its historical use in human and animal food to become a sustainable option in agriculture and livestock production, thanks to its drought resistance, its ability to grow in degraded soils, and its contribution to improving soil structure and water retention (SEMARNAT, 2020). Due to its nutritional composition rich in fiber, water, carbohydrates, proteins, vitamins, and minerals, forage prickly pear cactus has become a valuable feed supplement for cattle, goats, and sheep, especially in regions with limited water and pasture (SADER, 2022).

Historically, in Mexico, forage cactus has been used as livestock feed since the colonial period, particularly in arid areas where the scarcity of conventional pastures encouraged its use to sustain cattle during dry seasons (Cervantes de Salazar, 1991). This tradition has persisted and evolved through the promotion of its cultivation to support animal feeding in arid regions, recognizing its capacity to meet part of the water requirements of livestock in hot climates and to contribute to cattle food security (Anaya-Pérez & Bautizta-Zane, 2008). In Chihuahua, particularly in the south-central region, extensive cattle production is fundamental to the local economy; however, it faces increasing challenges associated with drought, soil degradation, and rising feed costs. These factors negatively affect the sustainability and competitiveness of the sector (Lagos-Gómez *et al.*, 2014).

National forage cactus production reflects its strategic importance: in 2022, approximately 12,081 hectares were cultivated, yielding close to 130,000 tons with an average productivity of 10.8 tons per hectare. This generated a significant economic value of around 62 million pesos, with the state of Coahuila as the main producer (SIAP, 2023). These figures highlight the relevance of this crop as a feed resource in arid and semi-arid regions. From an economic perspective, the use of forage cactus can reduce feed costs in livestock production by 40-60%, given that feeding accounts for up to 70% of the total cost of this activity (Salazar, 2021). Furthermore, its simple management and low technological requirements make its production accessible to small-scale producers, encouraging adoption in rural communities with limited resources (Pedraza-Reyes *et al.*, 2023).

Therefore, considering the climatic and economic challenges affecting cattle fattening systems, it is pertinent to develop productive strategies that promote forage cactus as a sustainable forage alternative. This crop would not only improve the availability and quality of feed for livestock, but also contribute to water conservation and the rehabilitation of degraded soils, offering an integrated solution for producers seeking to enhance the resilience and economic viability of their production systems. In this context, the present study aimed to establish a forage cactus (*Opuntia ficus-indica*) production system adapted to

local conditions, providing a replicable model that supports agricultural sustainability and the socioeconomic well-being of small- and medium-scale producers in the study region.

MATERIALS AND METHODS

Study site location

The study was conducted in Delicias, Chihuahua, Mexico (28° 09' 46" N and 105° 27' 03" W). The dominant vegetation in the region includes semi-arid grasslands and native species such as mesquite (*Prosopis* spp.) and huisache (*Acacia farnesiana*) (Jurado-Guerra *et al.*, 2021). The prevailing soils are sandy, with low organic matter content (0.58% initial average) and a sandy clay loam texture in some areas (Cantú-Silva *et al.*, 2018).

The state of Chihuahua exhibits diverse climatic conditions: warm and dry in 40% of the territory, temperate semi-dry in 33%, and semi-cold subhumid in 24%. Temperatures range from 45 °C to −23 °C, with an annual mean of 17 °C. Rainfall is scarce, averaging 510 mm per year (Corrales-Suastegui *et al.*, 2025).

Biological material and crop establishment

The Copena variety of *Opuntia ficus-indica* was used as the biological material. Physiologically mature cladodes were established in a 500 m² area using a triangular (three-bolillo) planting pattern, with a spacing of 1 m between cladodes. Each cladode was inserted into the soil up to half its length to facilitate rooting and minimize the risk of dehydration. A drip irrigation system was implemented using perforated tapes designed to deliver 1.5 L h^{−1} during monthly sessions of 4.5 h, ensuring efficient water use. Manual weeding was performed to prevent competition for resources, formative pruning was carried out to promote uniform growth, and phytosanitary management was applied to prevent pest outbreaks, following the guidelines of the forage cactus technological package from INIFAP (2024).

Soil evaluation

Between April and November 2024, comparative soil analyses were conducted to assess soil evolution throughout the study period. In the initial analysis, key indicators such as organic matter, pH, texture, and available nutrients were determined. Subsequently, the same parameters were evaluated in the final analysis to identify changes attributable to the crop.

These physicochemical soil analyses were performed at the Soil Laboratory of the Faculty of Agricultural and Forestry Sciences at the Autonomous University of Chihuahua. Organic matter was determined using the Walkley-Black method, and pH was measured using the saturated paste technique. Available nutrients were quantified through specific procedures: nitrates (NO₃) as extractable nitrates, phosphorus (P) using the Olsen method, potassium (K) through ammonium acetate (AA) extraction, and the micronutrients iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) using the diethylenetriaminepentaacetic acid (DTPA) extraction method. Soil texture was characterized using the Richards method, and total calcium carbonate (CaCO₃) content was quantified through an acid analysis measuring the total carbonate concentration present in the sample.

Economic viability and financial analysis

The methodology proposed by Baca Urbina (2013) was applied to estimate economic viability, considering fixed, variable, and labor costs. In addition, the financial indicators Net Present Value (NPV), Internal Rate of Return (IRR), and the Cost-Benefit Ratio (CBR) were calculated in order to facilitate replication of the study under similar conditions and to extrapolate its results to other arid regions with comparable characteristics.

RESULTS AND DISCUSSION

Implementation of Forage Cactus Planting

The results obtained showed that propagation through cladodes proved to be an efficient technique, as it enabled the establishment of vigorous plants within a relatively short period. Irrigation frequency, adjusted to environmental conditions, contributed to optimizing water use without compromising growth. In addition, the application of practices such as formative pruning and the use of disinfected tools during crop management activities reduced the risk of diseases and promoted the expected product quality. Overall, crop establishment demonstrated that adequate land preparation, sanitary selection of plant material, and efficient water management positively influenced the initial development of forage cactus, laying the foundation for a sustainable and technically sound production system. These findings are consistent with those reported by González-Gaona *et al.* (2024), who indicated that deep mechanical soil preparation favors the initial establishment of forage cactus. Similarly, Navarro-Álvaro (2018) highlighted that land leveling improves irrigation efficiency, which aligns with the homogeneous water distribution observed in this plantation. Likewise, Robles-Contreras *et al.* (2008) emphasized the importance of soil analysis and agronomic management adapted to site-specific conditions, aspects reflected in the favorable crop response.

Design and installation of the irrigation system

Overall, the results showed that the implementation of drip irrigation enhanced water-use efficiency, improved soil moisture conditions, and strengthened crop establishment, consolidating it as a relevant alternative for production systems in areas with limited water availability. This approach proved more suitable than the traditional surface irrigation schemes commonly used in the region. Controlled flow application allowed adequate moisture conditions to be maintained with lower water volumes, representing a significant optimization of the resource. This response is consistent with Torres-Cobo (2024), who indicated that drip irrigation aligns well with forage cactus physiology by delivering water directly to the root zone. Similarly, the findings agree with López-Medina *et al.* (2024), who reported efficiencies above 90% and considerable reductions in water consumption under proper management. Under semi-arid conditions, the installed system demonstrated to be a technically viable strategy to enhance crop sustainability. Reduced losses through evaporation and runoff contributed not only to water savings but also to greater stability in forage cactus growth. Furthermore, the continuous and trouble-free operation reflected adequate hydraulic planning and system compatibility with site-specific terrain characteristics.

Positive variables

Organic matter

Two organic matter analyses were conducted, one prior to planting and the other after crop establishment. An increase was observed (Figure 1), indicating an improvement in soil fertility and suggesting more favorable conditions for crop development. The observed increase may be associated with the applied management practices and the integration of sustainable strategies, which evidenced greater biological activation of the soil and an enhancement of its potential fertility. This is essential for the development of forage cactus cultivation (Izquierdo-Bautista & Arévalo-Hernández, 2021). Organic matter improves the physical and chemical properties of the soil, including nutrient transport, moisture retention, aeration, and porosity. It also contributes to reducing bulk density (Brechtel, 2004).

Soil pH

Soil pH increased from 6.85 to 8.12 (Figure 2), approaching the range reported as optimal for forage cactus cultivation (8.34) according to Orona-Castillo *et al.* (2003). The observed increase may be attributed to a higher concentration of alkaline elements such as potassium and magnesium, which reached values of 396 mg kg^{-1} and 2.65 mmol L^{-1} , respectively (Rodríguez-González, 2014).

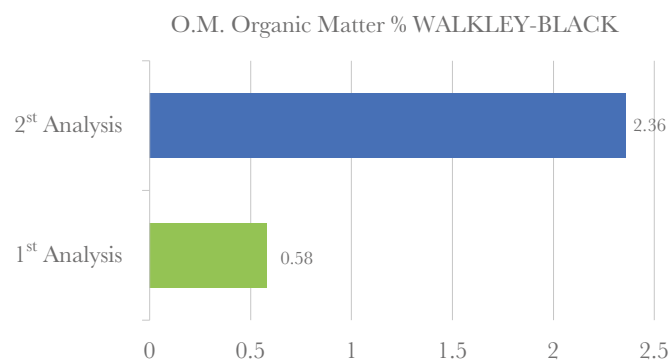


Figure 1. Organic matter increase. Source: Author's own elaboration.

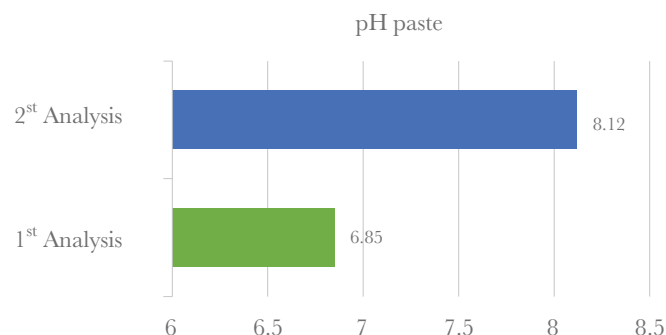


Figure 2. pH increase. Source: Author's own elaboration.

Together with the increase in organic matter, this shift changed the soil reaction from slightly acidic to alkaline, a condition that has been reported as favorable for the establishment and production of forage cactus (Rivera *et al.*, 2018).

Available Nutrients

Increases were recorded in the concentrations of nitrates, phosphorus, potassium, iron, zinc, and manganese, while copper remained constant (Table 1). These results were consistent with the increase observed in soil organic matter (Martínez-Nevárez *et al.*, 2024). Rodríguez and Flórez (2004) emphasize that these elements are essential for plants to complete their life cycle, and the absence of any one of them cannot be replaced by another.

Soil texture

Regarding soil texture, a change from sandy clay to sandy clay loam was observed. This texture type falls within the classes reported as suitable for forage cactus, which thrives in soils with a high calcium carbonate content and loamy textures, such as sandy loam or sandy clay loam (Ruiz-López, 2011). Likewise, Ruiz-Corral *et al.* (2013) indicated that optimal forage cactus growth occurs in sandy and sandy-clay soils, provided they are calcareous and have a high salt content, conditions that promote better crop development.

Variables to monitor

Total Calcium Carbonate (CaCO₃)

Total CaCO₃ content showed a decrease (Figure 3), dropping from 33.02% to 12.03%, which represented a reduction of 20.99%. This change should be considered in soil management, since low calcium carbonate levels may influence nutrient availability (Cruz-Macías *et al.*, 2020). Although forage cactus is a tolerant and adaptable species, marked reductions in this component could affect its development if appropriate fertilization strategies are not implemented (López-Collado *et al.*, 2013).

Economic Viability

The initial investment required was \$50,000 MXN, allocated to land preparation and conditioning, installation of the drip irrigation system, and the acquisition of basic tools

Table 1. Increases in available nutrients.

Available Nutrient (mg kg ⁻¹)		1 st analysis	2 st analysis
NO ₃	Nitrates	2.03	35
P OLSEN	Phosphorus	1.25	38.02
K AC. AMONIO AA	Potassium	854	1250
Fe DTPA A.A	Iron	0.36	1.2
Zn DTPA A.A	Zinc	0.24	0.36
Cu DTPA A.A	Copper	0.21	0.21
Mn DTPA A.A	Manganese	1.02	2.36

All concentrations are reported in mg kg⁻¹ (ppm).

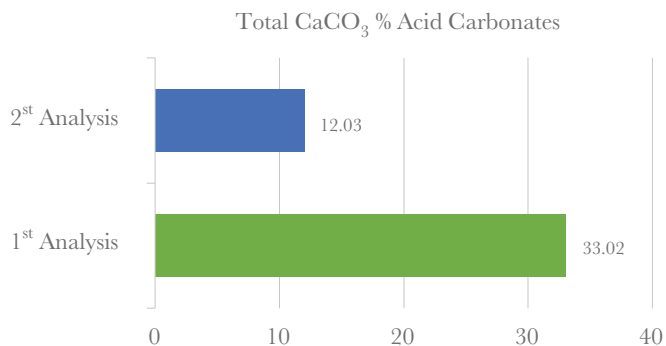


Figure 3. Decrease in Total CaCO Content. Source: Author’s own elaboration.

and equipment for operation. Annual fixed and variable costs were estimated at \$20,000 MXN, including crop management activities, maintenance of the irrigation system, and plant replacement.

Based on the projected yield and a selling price of \$3.25 per kg, the estimated annual income would allow recovery of the initial investment within an approximate period of three years.

Financial Analysis

The financial analysis was conducted over a five-year evaluation horizon using a 12% discount rate. The obtained indicators included a NPV of \$42,075.89 MXN, an IRR of 39.48%, and a BCR of 2.03. These results are presented in Table 2.

The financial projection showed favorable performance over the five-year evaluation period. Constant annual revenues of \$37,498.50 MXN were estimated, resulting in an annual net cash flow of \$17,498.50 MXN. During the first two years, the cumulative cash flow remained negative due to the recovery of the initial investment of \$50,000.00 MXN. The break-even point was reached in the third year, when the cumulative cash flow became positive. From that moment onward, the project generated net profits that increased overall profitability.

The discounted net cash flow indicated that, even when applying a 12% discount rate, the benefits exceeded both operating costs and the initial investment, thus confirming the economic viability of the productive model. These results are consistent with those reported by SAGARPA (2015), which estimated an investment of approximately

Table 2. Five-year financial projection.

Year	Revenue (MXN)	Costs (MXN)	Net Cash Flow (MXN)	Discounted Net Cash Flow (MXN)	Cumulative Cash Flow
1	37498.5	20000	17498.5	15623.66	-32501.5
2	37498.5	20000	17498.5	13949.7	-15003
3	37498.5	20000	17498.5	12455.09	2495.5
4	37498.5	20000	17498.5	11120.61	19994
5	37498.5	20000	17498.5	9929.12	37492.5

\$50,000.00 MXN per hectare in the states of Aguascalientes, Guanajuato, and Zacatecas, with cost recovery beginning in the third year and annual revenues of \$40,800.00 MXN. Similarly, Morales *et al.* (2016), in a business plan for forage cactus production in the state of Morelos, estimated an investment of \$49,000.00 MXN and confirmed medium-term recovery.

CONCLUSIONS

The forage cactus production system proved to be technically viable and economically profitable, supported by a strategic initial investment aimed at maximizing critical resources such as water in a context of recurrent droughts and soils deficient in organic matter and nutrients. The use of drip irrigation optimized water resources, promoting sustainability by reducing costs and increasing feed production. This confirms the feasibility of the project and establishes a precedent for future initiatives that prioritize water-use efficiency and profitability.

Furthermore, this model enables the conversion of low-fertility soils into productive land, taking advantage of the benefits of forage cactus, which has traditionally been considered a low-value crop. The results obtained are replicable in the south-central region of Chihuahua, Mexico, and may serve as a reference for producers interested in sustainable and profitable strategies.

REFERENCES

- Anaya-Pérez, M. A., y Bautizta-Zane, R. (2008). El nopal forrajero en México: del siglo XVI al siglo XX. *Agricultura, sociedad y desarrollo*, 5(2). https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1870-54722008000200001#:text=Nopal%20forrajero%20en%20el%20siglo,Flores%20y%20Aguirre%2C%201979.
- Baca-Urbina, G. (2013). Evaluación de Proyectos (séptima edición ed.). McGRAW-HILL/INTERAMERICANA EDITORES, S.A. DE C.V. https://www.uachatec.com.mx/wp-content/uploads/2019/05/LIBRO-Evaluaci%20n-de-proyectos-7ma-Edici%20n-Gabriel-Baca-Urbina-FREELIBROS.ORG_.pdf
- Brechelt, A. (2004). Manejo Ecológico del Suelo. Fundación Agricultura y Medio Ambiente, Red de Acción en Plaguicidas y sus Alternativas para América Latina, 4. https://bizibaratztea.eus/storage/liburutegia/dokumentuak/manejo_ecologico_del_suelo.pdf
- Cantú-Silva, I., Díaz-García, K., Yáñez-Díaz, M., González-Rodríguez, H., y Martínez-Soto, R. (2018). Caracterización fisicoquímica de un Calcisol bajo diferentes sistemas de uso de suelo en el noreste de México. *Revista Mexicana de Ciencias Forestales*, 9(49). <https://doi.org/10.29298/rmcf.v9i49.153>
- Cervantes de Salazar, F. (1991). México en 1554 y Tumulo Imperial. México: Porrúa.
- Corrales-Suastegui, A., González-Jasso, L., Chávez-Sánchez, N., y Contreras-García, P. (2025). Evaluación de la precipitación y temperatura simuladas por el modelo WRF en el estado de Chihuahua. *Revista Politécnica de Aguascalientes*, 5, 1-7. https://revistapolitecnicaags.upa.edu.mx/wp-content/uploads/2025/05/V4116_.pdf
- Cruz-Macías, W., Rodríguez-Larramendi, L., Salas-Marina, M., Hernández-García, V., Campos-Saldaña, R., Chávez-Hernández, M., y Gordillo-Cueriel, A. (2020). Efecto de la materia orgánica y la capacidad de intercambio catiónico en la acidez de suelos cultivados con maíz en dos regiones de Chiapas, México. *Terra Latinoamericana*, 38(3), 475-480. <https://doi.org/10.28940/terra.v38i3.506>
- Flores-Ortiz, M. A., y Reveles-Hernandez, M. (2010). Producción de Nopal Forrajero de Diferentes Variedades y Densidades de Plantación. *RES PYN Revista Salud Pública y Nutrición*, 198-210. https://produccion-animal.com.ar/produccion_y_manejo_pasturas/Tuna/15-nopal_forrajero.pdf
- Gutiérrez-Luna, R., Rodríguez-Tenorio, D., Martínez-Trejo, G., Aguirre-Calderón, C., y Sánchez-Gutiérrez, R. (2012). Bancos de Proteína para Rumiantes en el Semiárido Mexicano. Instituto Nacional de Investigaciones, Forestales, Agrícolas y Pecuarias. (47), 30. <https://zacatecas.inifap.gob.mx/publicaciones/bancpro.pdf>

- INIFAP. (2024). Componentes Tecnológicos para el cultivo del Nopal. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. http://inifapnortecentro.gob.mx/nodos/paquetes_tecnologicos/2024/zacatecas/PAQUETE_TECNOLÓGICO_NOPAL_TUNERO.pdf
- Izquierdo-Bautista, J., y Arévalo-Hernández, J. J. (10 de agosto de 2021). Determinación de la materia orgánica del suelo (MOS) por el método químico y por calcinación. *Revista Ingeniería y Región*, 26, 20-28. <https://doi.org/10.25054/22161325.2527>
- Jurado-Guerra, P., Velázquez-Martínez, M., Sánchez-Gutiérrez, R., Álvarez-Holguín, A., Domínguez-Martínez, P., Gutiérrez-Luna, R., . . . Chávez-Ruiz, M. (2021). Los pastizales y matorrales de zonas áridas y semiáridas de México: Estatus actual, retos y perspectivas. *Revista Mexicana de Ciencias Pecuarias*, 12, 261-285. <https://doi.org/10.22319/rmcp.v12s3.5875>
- Lagos-Gómez, H., González-González, F. J., y Castillo-Rangel, F. (2014). Paquete Tecnológico para la engorda de ganado bovino en corral. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, 1. <https://www.producechihuahua.org/paqs/PT-0011EngordaGanado.pdf>
- Lara-Pulido, J. A., Guevara-Sanginés, A., y Torres-Rojo, J. M. (2020). Análisis económico para la transición a sistemas de producción ganadera regenerativa de bovinos en Chiapas, Chihuahua, Jalisco y Veracruz, México. Fondo Mexicano para la Conservación de la Naturaleza AC. <https://fmcn.org/uploads/publication/file/pdf/GANARE/Analisis%20Costos.pdf>
- López-Collado, C. J., Malpica-Vázquez, A., García-Pérez, E., y Sol-Sánchez, Á. (mayo de 2013). Crecimiento de *Opuntia ficus-indica* (L.) Mill. en la zona central de Veracruz. *Revista mexicana de ciencias agrícolas*, 4. https://www.scielo.org.mx/scielo.php?pid=S2007-09342013000900012&script=sci_arttext
- López-González, J. J. (2008). Caracterización e identificación de nopal forrajero en el noreste de México. *Revista Salud Pública y Nutrición* (5), 21-36. <http://repositorio.uaaan.mx:8080/xmlui/handle/123456789/47657>
- Martínez-Nevárez, L.-E., Prieto-Ruiz, J. Á., Sigala-Rodríguez, J. Á., García-Rodríguez, J. L., Martínez-Reyes, M., Carrillo-Parra, A., y Domínguez-Calleros, P. A. (2024). Crecimiento y Eficiencia en el Uso de Nutrientes de Plantas de *Pinus cooperi* C. E. Blanco Producidas en Vivero con un Fertilizante de Liberación Controlada. *Terra Latinoamericana*, 41. <https://doi.org/10.28940/terra.v41i0.1707>
- Morales, R., Pliego, P., Ramos, R., Rojas, I., y Barriga, G. (2016). Plan Delaware Negocio: Modelo orgánico y de valor agregado para el nopal. *AgroDer y Conservación Internacional-México*. <https://doi.org/10.13140/RG.2.2.33247.38565>
- Navarro-Álvaro, M. (2018). Nivelación de tierras: una opción viable para el uso eficiente y gestión sustentable del agua en la agricultura. *Revista Ingeniería y Región*, 20(1), 103-110. <https://doi.org/10.25054/22161325.2504>
- Orona-Castillo, I., Flores-Hernández, A., Rivera-González, M., Martínez, J. G., y Espinoza-Arellano, J. d. (junio de 2003). Productividad del Agua en el Cultivo del Nopal por Riego por Goteo en la Comarca Lagunera. *Terra Latinoamericana*, 21(2), 195-205. <https://www.redalyc.org/pdf/573/57315595006.pdf>
- Pedraza-Reyes, K., Pérez-Olvera, M., Navarro-Garza, H., y Espejel-García, A. (2023). El sistema familiar de producción de nopal verdura (*Opuntia ficus indica* L.) en San Pablo Ixquiltán, Méx. Importancia y estrategias de funcionamiento. *Revista De Geografía Agrícola* (72), 1-15. <https://doi.org/10.5154/rga.2023.72.2>
- Rivera, E., Magali, S., y Hercilia, D. (23 de junio de 2018). pH como factor de crecimiento en plantas. *Revista de Iniciación Científica*, 4(2), 102. <https://doi.org/10.33412/rev-ric.v4.0.1829>
- Rodríguez S., M., y Flórez R., V. (2004). Elementos Esenciales y Beneficiosos. CYTED Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo, 25-36. <http://hdl.handle.net/10835/3133>
- Rodríguez-González, H. R. (2014). Evaluación agronómica con enfoque agroecológico en un sistema diversificado de guayaba (*Psidium guajava* L.), nopal (*Opuntia ficus* L.), piña (*Ananas comosus* L.) y papaya (*Carica papaya* L.). Universidad Nacional Agraria. https://www.researchgate.net/publication/317132039_Evaluacion_agronomica_con_enfoque_agroecologico_en_un_sistema_diversificado_de_guayaba_Psidium_guajava_L_nopal_Opuntia_ficus_L_pina_Ananas_comosus_L_y_papaya_Carica_papaya_L_utilizando_vermicompost_Ma
- Ruiz-Corral, J. A., Medina, G.-G., González-Acuña, I. J., Ernesto, F.-L. H., Ramírez-Ojeda, G., Ceferino, O.-T.,... Byerly-Murphy, K. F. (2013). Requerimientos Agroecológicos de Cultivos (2 ed., Vol. 3). Jalisco: Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro de Investigación Regional Pacífico Centro. https://www.researchgate.net/profile/Jose-Ruiz-Corral/publication/343047223_REQUERIMIENTOS_AGROECOLOGICOS_DE_CULTIVOS_2da_Edicion/links/5f1310e04585151299a4c447/REQUERIMIENTOS-AGROECOLOGICOS-DE-CULTIVOS-2da-Edicion.pdf

- Ruiz-López, S. (2011). El nopal: propiedades y paquete tecnológico para su producción. Divulgación, Fundación Produce Sinaloa, A.C. <https://www.fps.org.mx/portal/index.php/publicaciones/106-otros/1226-el-nopal-propiedades-y-paquete-tecnologico-para-si-produccion>
- SADER. (2018). Secretaría de Agricultura y Desarrollo Rural. Los granos, cereales y plantas forrajeras: <https://www.gob.mx/agricultura/articulos/los-granos-cereales-y-plantas-forrajeras>
- SADER. (2022). Secretaría de Agricultura y Desarrollo Rural. Proyecto nopal forrajero: para mejorar la alimentación del ganado bovino: <https://www.gob.mx/agricultura/sanluispotosi/articulos/proyecto-nopal-forrajero-para-mejorar-la-alimentacion-del-ganado-bovino?idiom=es>
- SAGARPA. (2015). Estudio de Factibilidad para el Establecimiento de Cultivo de Nopal (Opuntia) en Tierras Ociosas de los Estados de Aguascalientes, Guanajuato y Zacatecas, Integrando un Catálogo de Paquetes Tecnológicos con Fines Alimenticios, Energéticos y Ambientales. Ejecutivo, Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. https://www.gob.mx/cms/uploads/attachment/file/346983/Nopal_ejecutivo.pdf
- Salazar, L. (2021). Universidad Autónoma de Nuevo León Facultad de Agronomía. El nopal clave nutrimental para ganado del sur de Nuevo León: <https://agronomia.uanl.mx/noticias/es-nopal-clave-nutrimental-para-ganado-del-sur-de-nuevo-leon/#:~:text=Una%20especie%20de%20nopal%20forrajero,el%20sorgo%20y%20el%20alfalfa>.
- SEMARNAT. (2020). Secretaría de Medio Ambiente y Recursos Naturales. La riqueza del nopal: <https://www.gob.mx/semarnat/articulos/la-riqueza-del-nopal>
- SIAP. (2023). Servicio de Información Agroalimentaria y Pesquera. Nopal, cifras y datos sobre esta ancestral planta: <https://www.gob.mx/siap/articulos/y-elnopal-ingreso-en-la-dieta-simbolica-y-real-de-los-mexicanos>



Ideal particle size in the main ingredients in pig feed

Martínez-Aispuro, José A.¹; Nieto-Aquino, Rafael^{2*}; Figueroa-Velasco, José L.¹; Sánchez-Torres, María T.¹; Cordero-Mora, José L.¹; Ayala-Monter, Marco A.³

¹ Colegio de Postgraduados, Campus Montecillo, Programa de Ganadería, Texcoco, Estado de México, México, C.P. 56264.

² Universidad Autónoma de San Luis Potosí. Facultad de Agronomía y Veterinaria, México, C.P. 78321. Soledad de Graciano Sánchez, S.L.P.

³ Universidad Autónoma de Guerrero, Facultad de Medicina Veterinaria y Zootecnia 2, Cuajinicuilapa, Guerrero, México. C.P. 41940.

* Correspondence: rafael.nieto@uaslp.mx

ABSTRACT

Objective: To determine the optimal particle size of the primary ingredients used in pig feed.

Design/methodology: A literature review was conducted to identify the optimal particle size of corn, sorghum, and soybean meal in pig diets.

Results: The optimal ingredient particle size by production stage is as follows: transition, 339-534 μm ; Initiation I, 339-534 μm in pellets or 305 μm in meal form; Initiation II, 920-943 μm ; and growth-finishing, 500-700 μm .

Study implications: The optimal particle size of all grains included in the diet should be evaluated across particle-size strata, as most studies assess only the mean particle size of a single ingredient.

Conclusions: Fine grinding enhances feed digestibility in pigs, which is reflected in improved productive performance. However, excessively small particle size for a given production stage may adversely affect intestinal health.

Keywords: swine production, milling, pellets, meal.

Citation: Martínez-Aispuro, J. A., Nieto-Aquino, R., Figueroa-Velasco, J. L., Sánchez-Torres, M. T., Cordero-Mora, J. L., & Ayala-Monter, M. A. (2026). Ideal particle size in the main ingredients in pig feed. *Agro Productividad*. <https://doi.org/10.32854/xqgwdf34>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: October 7, 2025.

Accepted: January 9, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February, 2026. pp: 205-213.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Ingredient milling is a processing operation in which the particle size of a feed ingredient is reduced. Its primary purpose is to decrease particle size to facilitate intake and enhance the nutritional availability of dietary fractions. This, in turn, increases the feed's contact surface area, making it more accessible to digestive enzymes and consequently improving feed efficiency. Ingredient milling also confers additional advantages, including improved mixing capacity and uniformity, reduced segregation during bulk transport, increased starch gelatinization, and enhanced pellet quality. However, producing excessively fine



ingredients can increase production costs, intensify contamination from generated dust, and induce functional alterations in the pigs' gastrointestinal tract (Almeida *et al.*, 2021). Therefore, the objective of this work was to synthesize available evidence on the ideal particle size achieved during the milling process for the main ingredients used in pig feeding, based on an analysis of publicly available results.

The milling process

Milling quality is assessed through factors such as feed particle homogeneity, uniformity, and size (Kiarie and Mills, 2019). One of the principal challenges in manufacturing feed for non-ruminants is achieving mixture uniformity and homogeneity, namely, controlling particle-size distribution (Goodarzi Borojeni *et al.*, 2016; Vukmirovic *et al.*, 2017).

An appropriate ingredient particle size is beneficial for feed-manufacturing processes such as mixing and hydrothermal treatments, including pelleting, extrusion, and expansion (Kiarie and Mills, 2019). Recommendations regarding optimal particle size and particle-size distribution in pigs are inconsistent and vary by production stage, as they are influenced by factors such as the physical form of the feed (ingredient particle size is reduced during pelleting and nutrient digestibility improves), diet complexity, grain type, endosperm hardness, the milling method (hammer mill, roller mill, multicracker, or multistage grinding), and pellet quality (Al-Rabadi *et al.*, 2017; Vukmirovic *et al.*, 2017).

From an economic standpoint, a particle-size distribution tailored to the animal's physiological requirements enables optimal nutrient utilization and improvements in productive outcomes. Nevertheless, more intensive grinding entails higher production costs, particularly due to the energy required to achieve smaller particle sizes (Almeida *et al.*, 2021).

In addition to increased energy consumption, grinding capacity and flowability decline, dust-related problems intensify, and excessively fine particles are associated with detrimental effects on the health and function of the gastrointestinal tract. The effectiveness of particle-size reduction also depends on factors such as the physical form of the feed (meal or pellet), whether it is offered to healthy animals, the animal's age, the raw materials used, the type of facilities, and even genetics. For example, because feed compaction increases when particle size falls below 500 μm , flowability may be impaired. This can be exacerbated in diets supplemented with oils and in silos or conveying lines with certain characteristics, ultimately leading to reduced feed intake (Scianca, 2021).

Effect of particle size on nutrient digestibility

Reducing the particle size of feed raw materials increases the exposed surface area for digestive enzymes, thereby enhancing nutrient digestibility and absorption; in turn, this may improve pigs' productive performance (Kiarie and Mills, 2019; Huting *et al.*, 2021).

Decreasing the particle size of corn, sorghum, and soybean meal has been associated with improvements in pigs' productive performance due to greater nutrient digestibility and enhanced feed efficiency (FE) (Kim *et al.*, 2016; Dzierva *et al.*, 2023). Physiological differences attributable to the particle size of the offered feed may be related to age-dependent endogenous enzyme production (Scianca, 2021). Reducing particle size

in ingredients improves starch digestibility by increasing grain surface area, which subsequently intensifies interaction with digestive enzymes (Huang *et al.*, 2015; Rojas and Stein, 2015; Rojas *et al.*, 2016a). Accordingly, the apparent ileal digestibility of starch and the gross energy of corn increase in growing pig diets as particle size is reduced from 865 to 339 μm (Rojas and Stein, 2015).

Although starch and energy digestibility may improve, the effects of particle-size reduction on nitrogen and amino acid digestibility in ingredients are inconsistent. Reducing corn particle size (400, 600, 800, and 1000 μm) in diets for growing pigs increased protein digestibility as particle size decreased (Ma *et al.*, 2021). However, reducing corn particle size did not improve the digestibility of most amino acids in weaned or growing pigs (Huang *et al.*, 2015; Rojas and Stein, 2015). Fastinger and Mahan (2003) reported that reducing soybean meal particle size (900, 600, 300, and 150 μm) increased amino acid digestibility by only 1% at a particle size of 600 μm . Table 1 summarizes studies evaluating different production stages of finishing pigs fed diets containing the main ingredients used in the Mexican feed industry, milled to diverse particle sizes.

During Initiation I [7-8 kg initial live weight (ILW)], a smaller particle size for corn and soybean meal (305-534 μm) increases the digestibility of energy and ether extract (Almeida *et al.*, 2021; Dzierva *et al.*, 2023; Almeida *et al.*, 2022; Huang *et al.*, 2015); however, an excessively reduced particle size may cause problems related to intestinal permeability (Huang *et al.*, 2015). For Initiation II (10-12 kg ILW), the optimal corn particle size depends on feed presentation (pellet or meal). Almeida *et al.* (2021) found that, at this stage, 943 μm is optimal for improving dry matter and ether extract digestibility. In contrast, Dzierva *et al.* (2023) reported that the best particle size for pelleted corn would be 696 μm to increase ether extract digestibility.

Although the particle size in that study is smaller than that reported by Almeida *et al.* (2021), both studies converge in indicating that the optimal particle size to improve productive performance lies between 920 and 943 μm . Conversely, when corn is offered as meal to pigs in Initiation II, a smaller particle size (400 μm) appears more appropriate to improve the digestibility of energy, dry matter, protein, and fiber (Ma *et al.*, 2021).

For the growth stage (20-34 kg), the evidence compiled in this review indicates that the particle size of the main macronutrient ingredients incorporated into the diet (corn and soybean meal) falls within 511-600 μm in both meal and pelleted forms, as this range provides a balance between nutrient digestibility and feed efficiency (Gao *et al.*, 2021; Jo *et al.*, 2021). A particle size below 511 μm does not improve nutrient digestibility (Gao *et al.*, 2021), whereas a particle size above 600 μm also fails to improve nutrient digestibility (Jo *et al.*, 2021). Gao *et al.* (2020) observed that reducing the mean particle size of corn and soybean meal from 511 to 390 μm in diets for growing pigs neither modified nutrient utilization nor affected the activity of amylase, trypsin, and chymotrypsin. Considering the mean particle size of the diet's macro-ingredients, Gao *et al.* (2020) recommend a mean particle size of 511 μm in corn-soybean diets to enhance productive performance and dietary nutrient-use efficiency in growing pigs, as particle sizes below 390 μm do not improve nutrient utilization; likewise, they indicate that it is not necessary to reduce the mean particle size of corn below 682 μm . Their results further show that the mean

particle size of duodenal digesta, ileal digesta, and feces decreased with particle-size reduction (511 vs. 390 μm), but mean particle size did not affect digestibility (total tract, energy, protein, ether extract, and fiber).

Additionally, reducing corn particle size (400, 600, 800, and 1000 μm) in diets for growing pigs increased the digestibility of energy, protein, dry matter, and fiber as corn particle size decreased (Ma *et al.*, 2021). Particle-size reduction improved energy digestibility in growing-finishing pigs fed sorghum (1062, 802, or 471 μm ; Owsley *et al.*, 1981). Moreover, in finishing pigs, corn particle size should be <618 μm to increase both energy and fiber digestibility (Lyu *et al.*, 2020).

Effect of particle size on productive performance

Reducing particle size increases the availability of certain nutrients, which may subsequently enhance pigs' productive performance (Lancheros *et al.*, 2020). The ideal particle size depends on the grain type used in the diet, the physical form of the feed (meal or pellets), and the pigs' growth phase.

In weaned piglets during the transition phase, reducing the particle size of corn and sorghum (300, 500, 700, and 900 μm) in pelleted feed linearly improved feed efficiency and average daily gain (ADG) during the first two weeks post-weaning for both ingredients; however, after these two weeks, the beneficial effect diminished, with the best feed efficiency observed at 500 μm . This suggests that, during the transition phase, responsiveness to particle-size reduction is greater in the first two weeks post-weaning, and that the optimal particle size for corn and sorghum increases with pig age after this period (Healy *et al.*, 1991).

Table 1 summarizes evidence on the effect of particle size on the productive parameters of finishing pigs. In Initiation I (initial live weight [ILW] of 7-8 kg), Dzierva *et al.* (2023) and Almeida *et al.* (2021) recommend corn particle sizes of 339 and 534 μm , respectively, for pelleted feed to increase feed efficiency. In contrast, Huang *et al.* (2015) reported that a corn particle size of 305 μm in meal improves ADG and dry matter intake (DMI). However, at this same stage, when soybean meal particle size was evaluated (1017 μm), a substantially larger particle size than that of corn was associated with increased ADG and feed intake. When pigs enter Initiation II (>10 kg), the mean particle size of pelleted feed increases relative to Initiation I, because a corn particle size between 920 and 943 μm increases DMI (Almeida *et al.*, 2021; Dzierva *et al.*, 2023) and ADG (Dzierva *et al.*, 2023). For pigs in the growth and finishing stages, the optimal corn particle size increases further. Jo *et al.* (2021), evaluating ground corn particle sizes of 600, 750, and 900 μm in diets for growing pigs, found that feed efficiency improved when a particle size of 600 μm was used. In growing-finishing gilts fed meal-based corn diets, feed efficiency decreased linearly as particle size was reduced (865, 677, 485, and 339 μm), with no effects on ADG or feed intake (Rojas *et al.*, 2016a). Nemechek *et al.* (2016) reported that reducing corn particle size in the complete diet from 650 to 350 μm in growing-finishing pigs resulted in decreased ADG, DMI, and feed efficiency when diets were provided as meal; however, pigs fed pelleted diets did not show negative effects on DMI or feed efficiency attributable to particle size. Regardless of whether pigs are fed

Table 1. Optimal particle size for ingredients supplied to fattening pigs.

Feed	Particle size (μm)	Observations	Stage	Author
Corn / Pellets	394, 534, 647, 695	↑ Feed efficiency (FE) at 534 μm .	Initiation (7 kg)	Almeida <i>et al.</i> (2021)
Corn / Pellets	339, 588	↑ FE and ↑ ether extract (EE) digestibility at 339 μm .	Initiation (7 kg)	Dzierva <i>et al.</i> (2023)
Soybean meal / Meal	411, 585, 1017	↑ Dry matter intake (DMI) and ↑ average daily gain (ADG) at 1017 μm ; ↑ digestible energy (DE) at 411 μm .	Initiation (7 kg)	Almeida <i>et al.</i> (2022)
Corn / Meal	305, 428	↑ ADG, ↑ DMI, and ↑ energy and EE digestibility at 305 μm ; however, ↓ intestinal permeability.	Initiation (8 kg)	Huang <i>et al.</i> (2015)
Corn / Pellets	587, 625, 798, 943	↑ DMI and ↑ dry matter (DM) and EE digestibility at 943 μm .	Initiation (12 kg)	Almeida <i>et al.</i> (2021)
Corn / Pellets	696-920	↑ DMI and ↑ ADG at 920 μm ; ↑ EE digestibility at 696 μm .	Initiation (11 kg)	Dzierva <i>et al.</i> (2023)
Corn / Meal	400, 600, 800	↑ energy, DM, crude protein (CP), and fiber digestibility as particle size decreased.	Initiation (10 kg) and Growth (36 kg)	Ma <i>et al.</i> (2021)
Sorghum / Meal or pellets	456, 890	↑ DMI with pellets; ↑ ADG and ↑ FE at 456 μm .	Growth (20 kg)	Al-Rabadi <i>et al.</i> (2017)
Corn-soybean meal / Pellets	390, 511, 682	Particle size did not modify nutrient utilization.	Growth (22 kg)	Gao <i>et al.</i> (2021)
Corn-soybean meal	600, 750, 900	↑ FE and ↑ incidence of keratinization at 600 μm .	Growth (22 kg)	Jo <i>et al.</i> (2021)
Corn / Meal or pellets	350, 650	↓ DMI and ↓ FE in meal form at 350 μm ; ↑ ADG at 650 μm .	Growth (34 kg)	Nemechek <i>et al.</i> (2016)
Corn / Meal	441, 543, 618, 659, 768	↑ energy digestibility as particle size decreased; ↑ fiber digestibility at 618 μm .	Finishing (53 kg)	Lyu <i>et al.</i> (2020)
Sorghum / Pellets	724, 573, 319	↑ FE and ↑ carcass yield at the smallest particle size.	Finishing (46 kg)	Paulk <i>et al.</i> (2015)

Abbreviations: FE, feed efficiency; EE, ether extract; CP, crude protein; DM, dry matter; DMI, dry matter intake; ADG, average daily gain; DE, digestible energy.

meal or pellets, they prefer diets manufactured with more coarsely ground corn (700 μm) (Gebhardt *et al.*, 2018). Conversely, for sorghum, a smaller particle size (319, 573, and 724 μm) in pelleted feed reduced feed intake and improved feed efficiency in finishing pigs (Paulk *et al.*, 2015).

The influence of ingredient particle size on pigs' productive performance is not consistent, and the underlying reasons are not fully understood. A major contributor to the observed variability and inconsistency in nutrient availability and productive responses is that most studies address mean particle size of ingredients or the diet. Lyu *et al.* (2021) found that the nutritional composition and physical characteristics of different particle-size strata of ground corn and soybean meal differ markedly, which helps explain differences in pigs' productive responses. Recognizing this issue, Al-Rabadi *et al.* (2017) ground sorghum using a 4-mm screen (890 μm), then separated and reground the coarser fraction of the ground sorghum (80%) using a 3.2-mm screen, achieving a more

homogeneous particle size (456 μm); this resulted in improved ADG and feed efficiency in growing pigs.

Effect of particle size on carcass quality

Reducing feed particle size improves carcass yield in pigs (Lancheros *et al.*, 2020) fed corn-based (Wondra *et al.*, 1995a; Rojas *et al.*, 2016a) and sorghum-based diets (Paulk *et al.*, 2015). A plausible explanation for the higher carcass yield observed in pigs fed finer particle sizes is reduced microbial fermentation, which in turn decreases intestinal tract weight (Rojas *et al.*, 2016b). With respect to backfat thickness and lean meat percentage, particle-size reduction does not appear to modify these variables (Paulk *et al.*, 2015; Rojas *et al.*, 2016a).

Effect of particle size on short-chain fatty acids

Most starch is digested in the small intestine; however, starch that escapes small-intestinal digestion is fermented in the large intestine, resulting in the synthesis of short-chain fatty acids (SCFAs) (Bach Knudsen, 2011). Therefore, reducing particle size may decrease SCFA production (Lancheros *et al.*, 2020). Rojas *et al.* (2016a) reported that feeding pigs finely ground corn (339-865 μm) reduced SCFA synthesis.

Effect of particle size on intestinal health

When high-grain diets are fed, there is a practical limit to how finely particles should be ground because excessive fineness increases acidity and pepsin activity due to an inadequate protective mucus layer in the esophageal region of the stomach. This negatively affects gastrointestinal health by increasing the incidence of gastric ulcers and gastric keratinization, which are common problems in the swine industry (Kiarie and Mills, 2019; Lancheros *et al.*, 2020). Fine grinding is associated with a higher incidence of ulcers and non-specific diarrhea in sows and in growing-finishing pigs (Wondra *et al.*, 1995a,b; Melnichouk, 2002). Brunsgaard (1998) indicated that particle size influences mucus production and composition (which protects against gastric infections) as well as gastrointestinal morphology, highlighting digestive disturbances and ulceration when grains are excessively ground. Notably, the issue appears to be driven less by mean particle size than by a higher proportion of extremely fine particles. Feeding high-grain diets based on finely ground ingredients increases acidity and pepsin activity due to the lack of a protective mucus layer in the esophageal region of the stomach (Varum *et al.*, 2010). Pigs fed diets containing corn ground to 400 μm exhibited a higher incidence of ulcers and parakeratosis than pigs fed diets containing corn ground to 1200 μm (Wondra *et al.*, 1995a). This aligns with findings in growing pigs, in which the incidence of parakeratosis increased as particle size decreased (600, 750, and 900 μm) in meal or pelleted feed (Jo *et al.*, 2021). However, ulcer development may not immediately impair productive performance in growing-finishing pigs, as reducing ground corn particle size to 339 μm increased the incidence of ulcers and tissue keratinization without affecting feed efficiency (Rojas *et al.*, 2016a). Therefore, paraqueratosis which precedes ulcer formation does not appear to be detrimental to pig growth.

Effect of particle size on pH and bacterial populations

The presence of coarse particles in the diet is important to ensure proper stomach function and a gradual transition of digesta from the stomach to the intestine (Huting *et al.*, 2021). In young piglets, larger feed particle size may influence the gastric emptying rate, because a slower nutrient transit from the stomach to the intestine reduces the risk of gastrointestinal infections; this results in a lower gastric pH due to the stomach's physical resistance to accommodating larger amounts of feed (Bornhorst *et al.*, 2013). Coarse particle size increases acidification in the stomach and the distal intestine, which may be beneficial for controlling the proliferation of enteric pathogens (Vukmirovic *et al.*, 2017), such as *Salmonella* or *Escherichia coli* (Kiarie and Mills, 2019).

Moreover, fine particles may promote undesirable intestinal outcomes, including colonization by *Streptococcus suis* in the stomach (Warneboldt *et al.*, 2016) and *Salmonella typhimurium* in the ileum (Hedemann *et al.*, 2005). Feeding pigs finely ground corn (339-865 μm) increased pH in the large intestine (Rojas *et al.*, 2016a). In pigs fed either a coarsely ground diet (671 μm) or a finely ground diet (217 μm), gastric pH was lower with the coarsely ground diet (pH 2.5) than with the finely ground diet (pH 5.0) (Warneboldt *et al.*, 2016).

CONCLUSIONS

Fine grinding can improve feed digestibility, feed efficiency, weight gain, and carcass yield in pigs; however, the optimal particle size depends on the production stage and the physical form of the feed. During the transition stage, the recommended particle size is 300 μm (pellets), and it increases gradually throughout the initiation period. The optimal particle size for Initiation I diets (7-8 kg initial live weight [ILW]) is 339-534 μm in pellets and 305 μm in meal form. In contrast, for pigs in Initiation II (10-12 kg ILW), the particle size of pelleted feed should be 920-943 μm .

For pigs in the growth-finishing stage, mean particle sizes between 500 and 700 μm are advisable. Furthermore, an excessively small particle size relative to each production stage may negatively affect pigs' intestinal health.

REFERENCES

- Almeida, L.M.; Zavelinski, V.A.B.; Sonálio, K.C.; da Silva, K.F.; Muramatsu, K.; Maiorka, A. (2021). Effect of feed particle size in pelleted diets on growth performance and digestibility of weaning piglets. *Livest. Sci.* 244, 104364. DOI: 10.1016/j.livsci.2020.104364
- Al-Rabadi, G.J.; Hosking, B.J.; Torley, P.J.; Williams, B.A.; Bryden, W.L.; Nielsen, S.G.; Black, J.L.; Gidley, M.J. (2017). Regrinding large particles from milled grains improves growth performance of pigs. *Anim. Feed Sci. Technol.* 233, 53-63. DOI: 10.1016/j.anifeedsci.2016.08.004
- Bach Knudsen, K.E. (2011). Triennial growth symposium: effects of polymeric carbohydrates on growth and development in pigs. *J. Anim. Sci.* 89, 1965-1980. DOI: 10.2527/jas.2010-3602
- Bornhorst, G.M.; Chang, L.Q.; Rutherford, S.M.; Moughan, P.J.; Singh, R.P. (2013). Gastric emptying rate and chyme characteristics for cooked brown and white rice meals *in vivo*. *J. Sci. Food Agric.* 93, 2900-2908. DOI: 10.1002/jsfa.6160
- Brunsgaard, G. (1998). Effects of cereal type and feed particle size on morphological characteristics, epithelial cell proliferation, and lectin binding patterns in the large intestine of pigs. *J. Animal Sci.* 76(11), 2787-2798. DOI: 10.2527/1998.76112787x
- Dzierva, L.; dos Santos, M.C.; de Almeida, L.M.; da Rocha, C.; Bassi, L.S.; Muramatsu, K.; Maiorka, A. (2023). Feed particle size and amylase supplementation in diets for nursery piglets: digestibility and growth performance. *Livest. Sci.* 271, 105211. DOI: 10.1016/j.livsci.2023.105211

- Fastinger, N.D.; Mahan, D.C. (2003). Effect of soybean meal particle size on amino acid and energy digestibility in grower-finisher swine. *J. Anim. Sci.* 81, 697-704. DOI: 10.2527/2003.813697x
- Gao, Q.; Zhao, F.; Dang, F.; Zhang, H.; Wang, Y. (2020). Effect of corn particle size on the particle size of intestinal digesta or feces and nutrient digestibility of corn-soybean meal diets for growing pigs. *Animals*. 10(5), 876. DOI: 10.3390/ani10050876
- Gebhardt, J.T.; Paulk, C.B.; Tokach, M.D.; DeRouchey, J.M.; Goodband, R. D.; Woodworth, J.C.; De Jong, J.A.; Coble, K.F.; Stark, C.R.; Jones, C.K., Dritz, S.S. (2018). Effect of roller mill configuration on growth performance of nursery and finishing pigs and milling characteristics. *J. Anim. Sci.* 96:2278-2292. DOI: 10.1093/jas/sky147
- Goodarzi Borojjeni, F.; Svihus, B.H.; von Reichenbach, G.; Zentek, J. (2016). The effects of hydrothermal processing on feed hygiene, nutrient availability, intestinal microbiota and morphology in poultry—A review. *Anim. Feed Sci. Technol.* 220:187-215. DOI: 10.1016/j.anifeedsci.2016.07.010
- Healy, B.J.; Hancock, J.D.; Kennedy, G.A.; Bramel-Cox, P.J.; Behnke, K.C.; Hines, R.H. (1994). Optimum particle size of corn and hard and soft sorghum for nursery pigs. *J. Anim. Sci.* 72, 2227-2236. DOI: 10.2527/1994.7292227x
- Hedemann, M.S.; Mikkelsen, L.L.; Naughton, P.J.; Jensen, B.B. (2005). Effect of feed particle size and feed processing on morphological characteristics in the small and large intestine of pigs and on adhesion of *Salmonella enterica* serovar Typhimurium DT12 in the ileum *in vitro*. *J. Anim. Sci.* 83, 1554-1562. DOI: 10.2527/2005.8371554x
- Huang, C.; Zang, J.; Song, P.; Fan, P.; Chen, J.; Liu, D.; He, P.; Ma, X. (2015). Effects of particle size and drying methods of corn on growth performance, digestibility and haematological and immunological characteristics of weaned piglets. *Arch. Anim. Nutr.* 69(1), 30-45. DOI: 10.1080/1745039X.2014.1002673
- Huting, A.M.; Middelkoop, A.; Guan, X.; Molist, F. (2021). Using nutritional strategies to shape the gastrointestinal tracts of suckling and weaned piglets. *Animals*. 11(2), 402. DOI: 10.3390/ani11020402
- Jo, Y.Y.; Choi, M.J.; Chung, W.L.; Hong, J.S.; Lim, J.S.; Kim, Y.Y. (2021). Effects of feed form and particle size on growth performance, nutrient digestibility, carcass characteristics, and gastric health in growing-finishing pigs. *Anim. Biosci.* 34(6), 1061. DOI: 10.5713/ab.20.0777
- Kiarie, E.G.; Mills, A. (2019). Role of feed processing on gut health and function in pigs and poultry: Conundrum of optimal particle size and hydrothermal regimens. *Front. Vet. Sci.* 6, 19. DOI: 10.3389/fvets.2019.00019
- Kim, J.S.; Ingale, S.L.; Baidoo, S.K.; Chae, B.J. (2016). Impact of feed processing technology on nutritional value of pigs feed: a review. *Anim. Nutr. Feed Technol.* 16(2), 181-196. DOI: 10.5958/0974-181X.2016.00017.2
- Lancheros, J.P.; Espinosa, C.D.; Stein, H.H. (2020). Effects of particle size reduction, pelleting, and extrusion on the nutritional value of ingredients and diets fed to pigs: a review. *Anim. Feed Sci. Technol.* 268, 114603. DOI: 10.1016/j.anifeedsci.2020.114603
- Lyu, Z.; Wang, L.; Wu, Y.; Huang, C. (2020). Effects of particle size and lipid form of corn on energy and nutrient digestibility in diets for growing pigs. *Asian-Australasian Journal of Animal Sciences*, 33(2), 286. DOI: 10.5713/ajas.19.0196
- Lyu, F.; van der Poel, A.F.B.; Hendriks, W.H.; Thomas, M. (2021). Particle size distribution of hammer-milled maize and soybean meal, its nutrient composition and *in vitro* digestion characteristics. *Anim. Feed Sci. Technol.* 281, 115095. DOI: 10.1016/j.anifeedsci.2021.115095
- Ma, D.; Zhu, T.; Yang, F.; Zhang, S.; Huang, C. (2021). Effects of corn particle size on energy and nutrient digestibility in diets fed to young pigs and adult sows. *Anim. Biosci.* 34(9), 1491. DOI: 10.5713/ab.20.0556
- Melnichouk, S.I. (2002). Mortality associated with gastric ulceration in swine. *Can. Vet. J.* 43(3), 223-225. <https://pubmed.ncbi.nlm.nih.gov/articles/PMC339211/>
- Nemecek, J.E.; Tokach, M.D.; Dritz, S.S.; Goodband, R.D.; DeRouchey, J.M.; Woodworth, J.C. (2016). Effects of diet form and corn particle size on growth performance and carcass characteristics of finishing pigs. *Anim. Feed Sci. Technol.* 214, 136-141. DOI: 10.1016/j.anifeedsci.2016.02.002
- Owsley, W.F.; Knabe, D.A.; Tanksley Jr, T.D. (1981). Effect of sorghum particle size on digestibility of nutrients at the terminal ileum and over the total digestive tract of growing-finishing pigs. *J. Anim. Sci.* 52, 557-566. DOI: 10.2527/jas1981.523557x
- Paulk, C.B.; Hancock, J.D.; Fahrenholz, A.C.; Wilson, J.M.; McKinny, L.J.; Behnke, K.C. (2015). Effects of sorghum particle size on milling characteristics and growth performance in finishing pigs. *Anim. Feed Sci. Technol.* 202, 75-80. DOI: 10.1016/j.anifeedsci.2015.01.017
- Rojas, O.J.; Stein, H.H. (2015). Effects of reducing the particle size of corn grain on the concentration of digestible and metabolizable energy and on the digestibility of energy and nutrients in corn grain fed to growing pigs. *Livest. Sci.* 181, 187-193. DOI: 10.1016/j.livsci.2015.09.013

- Rojas, O.J.; Liu, Y.; Stein, H.H. (2016a). Effects of particle size of yellow dent corn on physical characteristics of diets and growth performance and carcass characteristics of growing-finishing pigs. *J. Anim. Sci.* 94, 619-628. DOI: 10.2527/jas.2015-9054
- Rojas, O.J.; Vinyeta, E.; Stein, H.H. (2016b). Effects of pelleting, extrusion, or extrusion and pelleting on energy and nutrient digestibility in diets containing different levels of fiber and fed to growing pigs. *J. Anim. Sci.* 94, 1951-1960. DOI: 10.2527/jas.2015-0137
- Scianca, N.A. (2021). Tamaño de partícula y su influencia en la digestión en cerdos (Doctoral dissertation, Universidad Nacional de La Plata).
- Varum, F.J.O.; Veiga, F.; Sousa, J.S.; Basit, A.W. (2010). An investigation into the role of mucus thickness on mucoadhesion in the gastrointestinal tract of pig. *Eur. J. Pharm. Sci.* 40, 335-341. DOI: 10.1016/j.ejps.2010.04.007
- Vukmirovic, Đ.; Colovic, R.; Rakita, S.; Brlek, T.; Đuragic, O.; Solà-Oriol, D. (2017). Importance of feed structure (particle size) and feed form (mash vs. pellets) in pig nutrition—A review. *Anim. Feed Sci. Technol.* 233, 133-144. DOI: 10.1016/j.anifeedsci.2017.06.016
- Warneboldt, F.; Sander, S.J.; Beineke, A.; Valentin-Weigand, P.; Kamphues, J.; Baums, C.G. (2016). Clearance of *Streptococcus suis* in stomach contents of differently fed growing pigs. *Pathogens.* 5, 56. DOI: 10.3390/pathogens5030056
- Wondra, K.J.; Hancock, J.D.; Behnke, K.C.; Hines, R.H.; Stark, C.R. (1995a). Effects of particle size and pelleting on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. *J. Anim. Sci.* 73, 757-763. DOI: 10.2527/1995.733757x
- Wondra, K.J.; Hancock, J.D.; Kennedy, G.A.; Hines, R.H.; Behnke, K.C. (1995b). Reducing particle size of corn in lactation diets from 1200 to 400 micrometers improves sow and litter performance. *J. Anim. Sci.* 73, 421-426. DOI: 10.2527/1995.732421x

Altitudinal effect and multitemporal analysis of tree structure, distribution and richness in the Sierra Juárez of Ixtlán, Oaxaca, Mexico

Suárez-Mota Mario E.^{1*}; Hernández-Ruiz Alejandro¹; Paz-Aquino Omar¹; Bautista-Juárez Irene²

¹ Universidad de la Sierra Juárez. Laboratorio de Macroecología, Biogeografía y Análisis Espaciales de la Conservación Biológica. Avenida Universidad s/n. Barrio la Asunción, Ixtlán de Juárez, Oaxaca, México. C. P. 68725.

² Colegio de Posgraduados campus Montecillos. Carretera México-Texcoco Km. 36.5, Montecillo, Texcoco, Estado de México. C. P. 56264

* Correspondence: mesuarez@unsij.edu.mx

ABSTRACT

Objective: To determine the effect of altitude on tree structure, distribution, and species richness in the Sierra Juárez, Oaxaca, Mexico.

Design/methodology/approach: Satellite image analyses were conducted to assess the altitudinal effect and changes in vegetation health using the Normalized Difference Vegetation Index (NDVI).

Results: The relationship between biomes and altitude indicates that temperate forests at high elevations exhibit more than 55% species similarity. Tropical humid forests at lower elevations show approximately 48% similarity, while mountain humid forests at very high elevations present 45% similarity. Altitudinal and topographical effects in the Sierra Juárez are determining factors shaping the tree component.

Findings/Conclusions: This study contributes to the identification of altitudinal zones of tree assemblages distributed across different biomes.

Keywords: Comaltepec, Ixtepeji, Jaltianguis, NDVI, Oaxaca, UNSIJ.

Citation: Suárez-Mota, M. E., Hernández Ruiz, A., Paz-Aquino, O., & Bautista-Juárez, I. (2026). Altitudinal effect and multitemporal analysis of tree structure, distribution, and richness in the Sierra Juárez of Ixtlán, Oaxaca, Mexico. *Agro Productividad*. <https://doi.org/10.32854/fq0nrb52>

Academic Editor: Jorge Cadena
Iniguez

Associate Editor: Dra. Lucero del
Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre
Medina

Received: October 9, 2025.

Accepted: January 20, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February.
2026. pp: 215-231.

This work is licensed under a
Creative Commons Attribution-Non-
Commercial 4.0 International license.



INTRODUCTION

In Mexico, temperate ecosystems consist primarily of coniferous and oak forests that harbor high biological diversity distributed across broad areas, representing the cumulative effect of numerous regional differences in floristic composition, including several endemic and restricted-distribution species (Huerta-Martínez *et al.*, 2014). Various studies have addressed the structure, composition, richness, and diversity of temperate forests in different states of the country; however, analyses evaluating environmental and topographic parameters along altitudinal gradients remain relatively scarce (Sánchez-Gutiérrez, 2019; Holguín-Estrada *et al.*, 2021; García-García, 2023). Temperate ecosystems cover 17.4% of the national territory and are distributed across the Sierra Madre Oriental, Sierra Madre Occidental, Trans-Mexican Volcanic Belt, and Sierra Madre del Sur. They

form part of the typical vegetation of non-tropical latitudes, comprising vegetation that integrates distinct biomes and related ecosystems (Tamayo, 1990; Challenger, 2003). These temperate ecosystems depend not only on the presence of mountainous systems but also on climatic, edaphic, and orographic factors, as well as biogeographic history and the occurrence of specific floristic elements that are absent in temperate forests at higher elevations (Rzedowski, 1978; Challenger, 1998; Sánchez *et al.*, 2003; Holguín-Estrada *et al.*, 2021). Geographic variations such as climate, topography, and soil, which are associated with vegetation composition and structure, contribute to the establishment of boundaries between ecoregions (Torres-Robles *et al.*, 2015).

The influence of biotic and abiotic factors establishes species distribution patterns; likewise, structural analyses focus on understanding forest diversity in order to assess its response to different environmental changes (Cortés-Castelán & Islebe, 2005; Graciano-Ávila *et al.*, 2017). Vegetation and environmental conditions associated with ecoclimatic characteristics —such as radiation, precipitation, microrelief, and aspect— as well as microtopographic variables including steep slopes related to altitude and climate, affect soil properties and soil formation processes across landscapes, thereby determining vegetation assemblages typical of non-tropical latitudes (Llorente-Bousquets & Morrone, 2001; Sánchez *et al.*, 2003). Thus, the main factors determining the distribution of temperate ecosystems are altitude, rainfall abundance, and rainfall seasonality, which define the so-called ecological belts or distribution patterns (Challenger, 2003; Mazzola *et al.*, 2008). In contrast, the factors shaping the composition, diversity, and structure of plant communities depend on spatial scale, topographic features, temperature, and changes in precipitation levels associated with elevation (Cuyckens *et al.*, 2015).

Habitat fragmentation makes the implementation of classical sampling methodologies for assessing tree distribution and species richness more challenging. Currently, remote sensing has become a valuable tool because its spatial, spectral, radiometric, and temporal characteristics make it possible to measure biodiversity at large scales and to monitor ecosystem changes over time (Sánchez-Díaz, 2018).

In combination with field-based habitat data and land-cover maps derived from satellite image analysis, remote sensing enables more accurate estimation of species distribution, richness patterns, and temporal changes (Ledo *et al.*, 2012).

Vegetation distribution patterns are studied through latitudinal and altitudinal gradients of species richness, where transitions among different environmental variables represent gradients that may promote increases or decreases in vegetation cover and species frequency within a given area, considering elevation and range. Consequently, significant changes occur in floristic composition and community structure (Mazzola *et al.*, 2008; Zacarías-Eslava & Castillo, 2010; Valois-Cuesta *et al.*, 2016).

In a study conducted by Castellanos-Bolaños *et al.* (2010), it was established that tree species diversity and stand structure differ according to the phytosociological community. Similarly, Ruiz-Aquino *et al.* (2015), when evaluating the diversity and structure of a pine–oak forest in Ixtlán de Juárez, Oaxaca, determined that the analyzed species can coexist while modifying stand structure and horizontal distribution patterns. Currently, this type of research has gained importance for understanding natural species distribution

patterns under different environmental conditions and their influence on biological interactions and plant community dynamics in terms of structure and composition. Such studies contribute to biodiversity conservation, inform the management of commercially important tree species in forestry, provide botanical and ecological information to support sustainable management strategies, help predict potential areas of influence of invasive species, and anticipate shifts in species distribution ranges that may result from global climate change (Huerta-Martínez *et al.*, 2014; Sánchez-Gutiérrez *et al.*, 2019; Holguín-Estrada *et al.*, 2021; García-García *et al.*, 2023).

The satellite-derived Normalized Difference Vegetation Index (NDVI) is currently one of the most widely used analytical tools for interpreting multispectral imagery, primarily aimed at assessing vegetation condition and quantifying vegetation attributes (Huang *et al.*, 2021). Across multiple spatial resolutions, NDVI is considered one of the most reliable indicators of vegetation health, as it is calculated from the reflectance relationship between the red (R) and near-infrared (NIR) bands, which together contain more than 90% of the information related to Earth's vegetation (Baret *et al.*, 1989; Li *et al.*, 2021). Pesaresi *et al.* (2020), in evaluating NDVI time series to support phytosociological analyses, concluded that remote sensing makes it possible to differentiate and distinguish plant communities in an objective manner. Similarly, Zhu *et al.* (2011) used the Normalized Difference Vegetation Index to assess the spatial distribution of vegetation in the Qaidam Basin, identifying four factors affecting plant distribution in the area: precipitation, altitude, hydrological conditions, and human activities, which fragment the distribution pattern.

Matas-Granados *et al.* (2022) quantified vegetation changes over a 35-year period in protected areas hosting threatened plant species using NDVI, concluding that remote sensing-based monitoring can help assess the effects of slow processes and drastic events by identifying patterns across extensive regions, thereby supporting effective conservation actions. Structural modifications and spatial redistribution of plant communities are not driven solely by anthropogenic activities; climate change has also become a significant factor in recent years. Fayeche and Tarhouni (2021) analyzed the impact of climate variability on vegetation using the NDVI and precipitation data in the arid region of Gabes, finding that vegetation growth is strongly influenced by rainfall patterns. Knowledge of vegetation in relation to terrain topographic characteristics contributes to the establishment of restoration and management actions, as well as to the selection of species best adapted to specific ecological sites, thereby enhancing survival and promoting faster development (Díaz *et al.*, 2012). The objective of this study was to determine the effect of altitude on tree structure, distribution and species richness in the Sierra Juárez, Oaxaca, Mexico, through satellite image analysis to identify altitudinal effects and changes in vegetation health using the Normalized Difference Vegetation Index.

MATERIALS AND METHODS

Study Area

Ixtlán de Juárez is one of the 30 districts that constitute the state of Oaxaca. It comprises 154 localities distributed across 26 municipalities and is one of the three districts into which the Sierra Norte region is divided. The district is located at the

following extreme Universal Transverse Mercator (UTM) coordinates: 1,968,430.194 N; 805,198.532 E; 736,547.067 W; and 1,829,266.633 S, covering a total area of 2,885.54 km² (INEGI, 2023). The area encompasses diverse biomes, among which temperate forest, mountain cloud forest, and seasonally humid forest are prominent. The district boundaries were delineated using the open-access geographic information system QGIS version 3.4.8 (2019; Figure 1).

Data Acquisition

Tree species data were obtained from the National Biodiversity Information System (SNIB) of the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), a system developed to compile, organize, generate, and disseminate information on Mexico's biological diversity. The database is based on records of specimens collected in the country and housed in national and international scientific collections

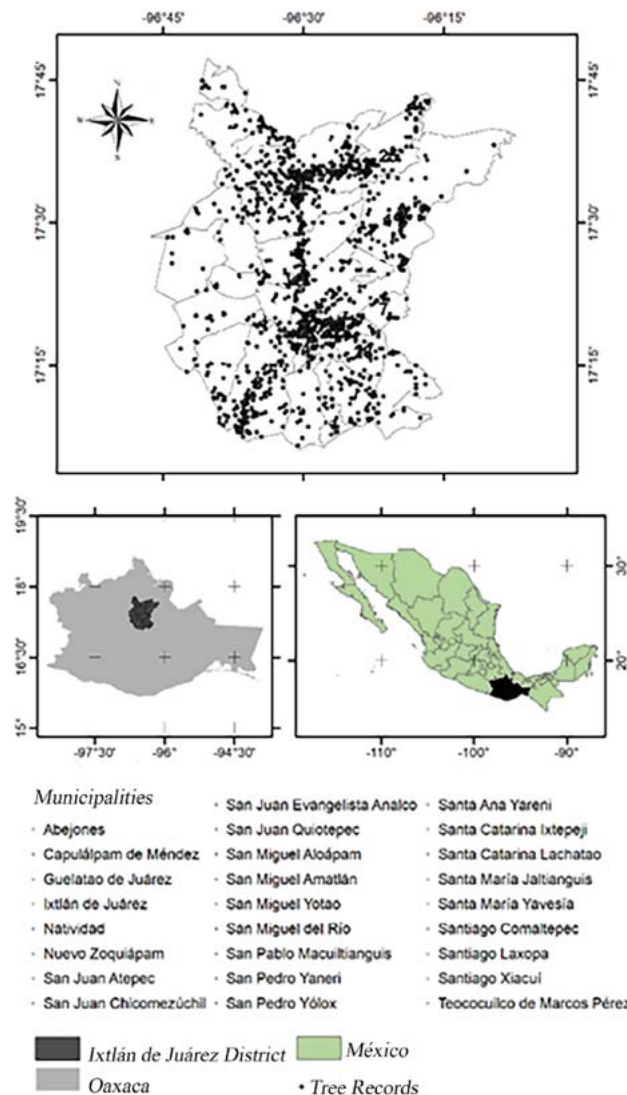


Figure 1. Geographic location of tree species in the District of Ixtlán, Oaxaca.

(SEMARNAT, 2018). Additionally, field records were collected, with particular emphasis on Ixtlán de Juárez and Santa Catarina Ixtepeji, as these municipalities exhibit a complex altitudinal gradient and sustain active forest management practices.

The consulted plant databases were curated to retain only species with tree and shrub life forms occurring within the District of Ixtlán. Duplicate records were removed, and specimen labels deposited in open-access scientific collections were reviewed, including the National Herbarium (MEXU) of the Universidad Nacional Autónoma de México. Field verification was also conducted in areas surrounding the Universidad de la Sierra Juárez, located in Ixtlán de Juárez, Oaxaca.

The cartographic layers used in this study included state political boundaries, municipal political boundaries, and land use and vegetation maps (INEGI, 2001, 2021, 2022; CONABIO, 2023). Based on the land use and vegetation data, biomes were defined according to the classification proposed by Suárez-Mota and Villaseñor (2011) and Villaseñor and Ortiz (2014). Agricultural areas, cultivated forests, human settlements, and water bodies were excluded from the analysis.

The Digital Elevation Model (DEM) was obtained from the official portal of the Instituto Nacional de Estadística y Geografía (INEGI, 2023) at a spatial resolution of 90 m. Using this dataset, the polygon corresponding to the District of Ixtlán was delineated. The altitudinal gradient was classified into five categories to assess its correspondence with the defined biomes. The selected species distribution data were overlaid onto these altitudinal classes for spatial analysis.

Image processing

Satellite imagery was obtained from Landsat 5, Landsat 7, and Landsat 8 corresponding to the years 1995, 2000, 2005, 2010, 2015, and 2023, sourced from the United States Geological Survey (USGS, 2023). Image selection for the study area was conducted using a cloud cover filter of <40%. The selected imagery covered four seasonal periods, each comprising three months: January-March, April-June, July-September, and October-December. This approach allowed for the assessment of seasonal variations in vegetation health throughout the year across the analyzed temporal intervals.

After downloading, each image was clipped using a mask layer corresponding to the polygon of the District of Ixtlán through a Geographic Information System (GIS), specifically QGIS version 3.4.8 (2019). Individual spectral bands were processed separately for each year, as combinations of the red and near-infrared bands were required to calculate the Normalized Difference Vegetation Index (NDVI). This index was used to detect differences in vegetation cover and to distinguish vegetated areas from rocky and deforested zones.

NDVI values were calculated to determine vegetation health within the study area. The index ranges from -1 to 1 ; values closer to 1 indicate healthier vegetation due to higher reflectance in the near-infrared spectrum and greater absorption in the red band, which is typically associated with vigorous green biomass (Suárez-Mota *et al.*, 2023). This procedure was applied to all analyzed years. For Landsat 5 and Landsat 7, as well as Landsat 8, the red

visible and near-infrared (NIR) bands were used according to the spectral configuration of each sensor. The NDVI was calculated using the following formula:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where: *NDVI*=Normalized Difference Vegetation Index; *NIR*=reflected light in the near-infrared spectrum; and *RED*=reflected light in the red portion of the spectrum.

Subsequently, using the Geographic Information System (GIS), the calculated NDVI values were extracted and assigned to the tree occurrence records, along with the corresponding altitudinal gradient values at which the collected data were located.

Data analysis

Frequency distributions and Kernel density plots were generated for the comparative analysis of NDVI values, biomes, and altitude using the *histogram* and *density* functions in SAS version 9.4 (SAS Institute Inc., 2013). Mean comparisons were evaluated using box-and-whisker plots generated with the *vbox* function in SAS[®] 9.4 (SAS Institute Inc., 2013). Similarity analyses were performed using PAST version 4.04 (Hammer *et al.*, 2001) and SAS[®] 9.4. In PAST, binary species data were processed to determine the similarity between biomes and altitudinal ranges using the Jaccard index, which evaluates similarity based on shared species presence (values closer to 100% indicate greater similarity). Species diversity indices, including Shannon, Simpson, and Dominance indices, were calculated, and beta diversity was estimated using the Whittaker index.

RESULTS AND DISCUSSION

Diversity and Altitude

Species distribution along the altitudinal gradient was not uniform; a greater number of species was recorded at mid and high elevations (539 and 530 species, respectively), whereas lower elevations exhibited fewer species (255 species; Table 1).

Regarding biomes, temperate forests and mountain cloud forests showed the highest species richness, with 726 and 508 species, respectively, while xerophilous scrubland

Table 1. Species richness by biome and altitudinal range.

Biome	Number of species	Altitudinal range (msnm)	Number of species
BHM	508	1) 126-736.4	255
BTEMP	726	2) 763.4-1346.8	335
BTES	172	3) 1346.8-1957.2	539
BTH	436	4) 1957.2-2567.6	530
MXE	6	5) 2567.6-3178	426

MCF=mountain cloud forest; TF=temperate forest; SDTF=seasonally dry tropical forest; THF=tropical humid forest; XS=xerophilous scrubland; 1=very low; 2=low; 3=medium; 4=high; 5=very high.

recorded only six species. These results indicate that higher altitudinal gradients associated with forested biomes tend to support greater species diversity. However, it is important to note that sampling effort was more concentrated along roadsides and surrounding accessible areas (Table 1), which may have influenced species records.

Analysis of the Tree Stratum of the District of Ixtlán Based on NDVI

A total of 24 NDVI images were generated from the proposed analysis, corresponding to four seasonal periods for each evaluated year (1995, 2000, 2005, 2010, 2015, and 2023). The results indicate that vegetation exhibited better health conditions in 1995 compared to 2023, as the latter showed an increase in disturbed vegetation indices.

NDVI values (Figure 2) ranged from -1 to 1 , with a color scale extending from red (disturbed vegetation) to green (healthy vegetation). In 2023 and January 2015, predominant colors were mainly red to yellow tones, indicating lower vegetation vigor. In contrast, January and May 1995, as well as May and July 2005, displayed greener tones (higher NDVI values), suggesting healthier vegetation conditions with fewer disturbed patches. A particular case was observed in July 2015, when NDVI values remained within a positive range. By November 2015, vegetation conditions appeared more balanced, with yellow-green tones predominating, the latter approaching values close to 1 (Figure 3).

Mean NDVI values indicate that the year 2000 exhibited one of the highest vegetation health levels, with a minimum value of -0.22 and a maximum of 0.77 . In contrast, 2005 showed comparatively lower vegetation health, with a minimum of -0.45 and a maximum of 0.56 (Table 2).

NDVI Density by Biome

Rainier months favor improved vegetation health. In 1995, NDVI values during the rainy season ranged from 0 to 0.8 , with the highest biome concentrations occurring

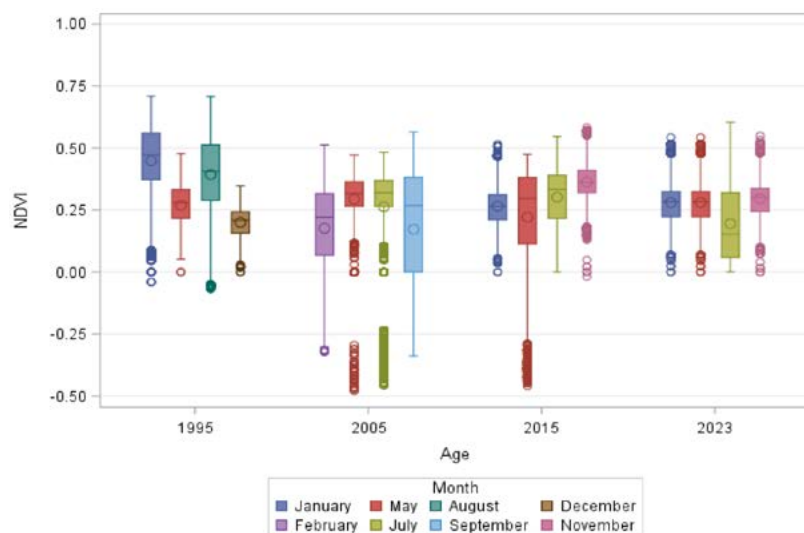


Figure 2. Ranges of Normalized Difference Vegetation Index (NDVI) values obtained from tree species records by month and year in the District of Ixtlán.

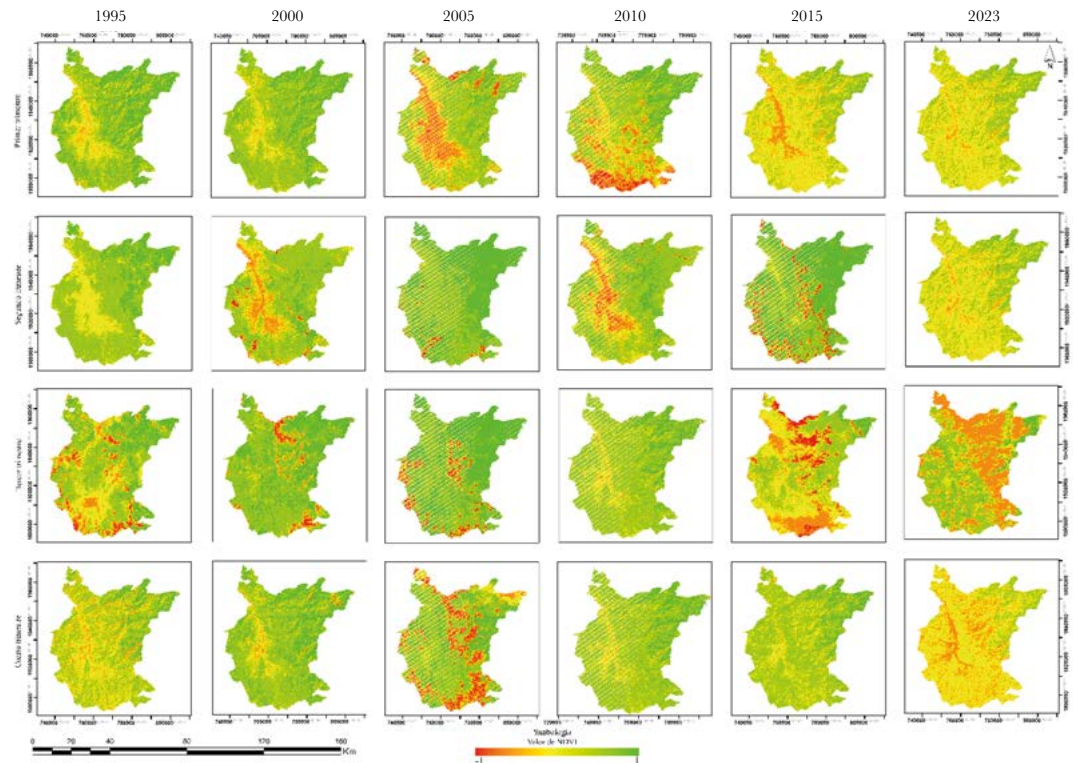


Figure 3. Normalized Difference Vegetation Index (NDVI) values for the District of Ixtlán in the years 1995, 2000, 2005, 2010, 2015, and 2023.

Table 2. Ranges of Normalized Difference Vegetation Index (NDVI) values obtained for the different years analyzed in the District of Ixtlán.

Year	Range of NDVI		
	Minimum	Average	Maximum
1995	-0.22325	0.196	0.6145
2000	-0.222	0.277	0.7755
2005	-0.45925	0.053	0.56525
2010	-0.44925	0.100	0.6495
2015	-0.19425	0.242	0.6785
2023	-0.13275	0.26	0.65175

between 0.2 and 0.6. Ten years later, during the same rainy months, NDVI values fluctuated between -0.4 and 0.5 , with greater density concentrated between 0.2 and 0.4 . By July 2023, NDVI values ranged from 0 to 0.6 ; however, the highest concentration occurred between 0 and 0.4 , indicating a progressive deterioration in vegetation condition over time. Changes in vegetation health are evident across the analyzed years. The mountain cloud forest exhibited a mean NDVI value of 0.5 during the rainy season in 1995, whereas in 2023 the mean decreased to 0.15 , reflecting a marked decline in vegetation health (Figure 4).

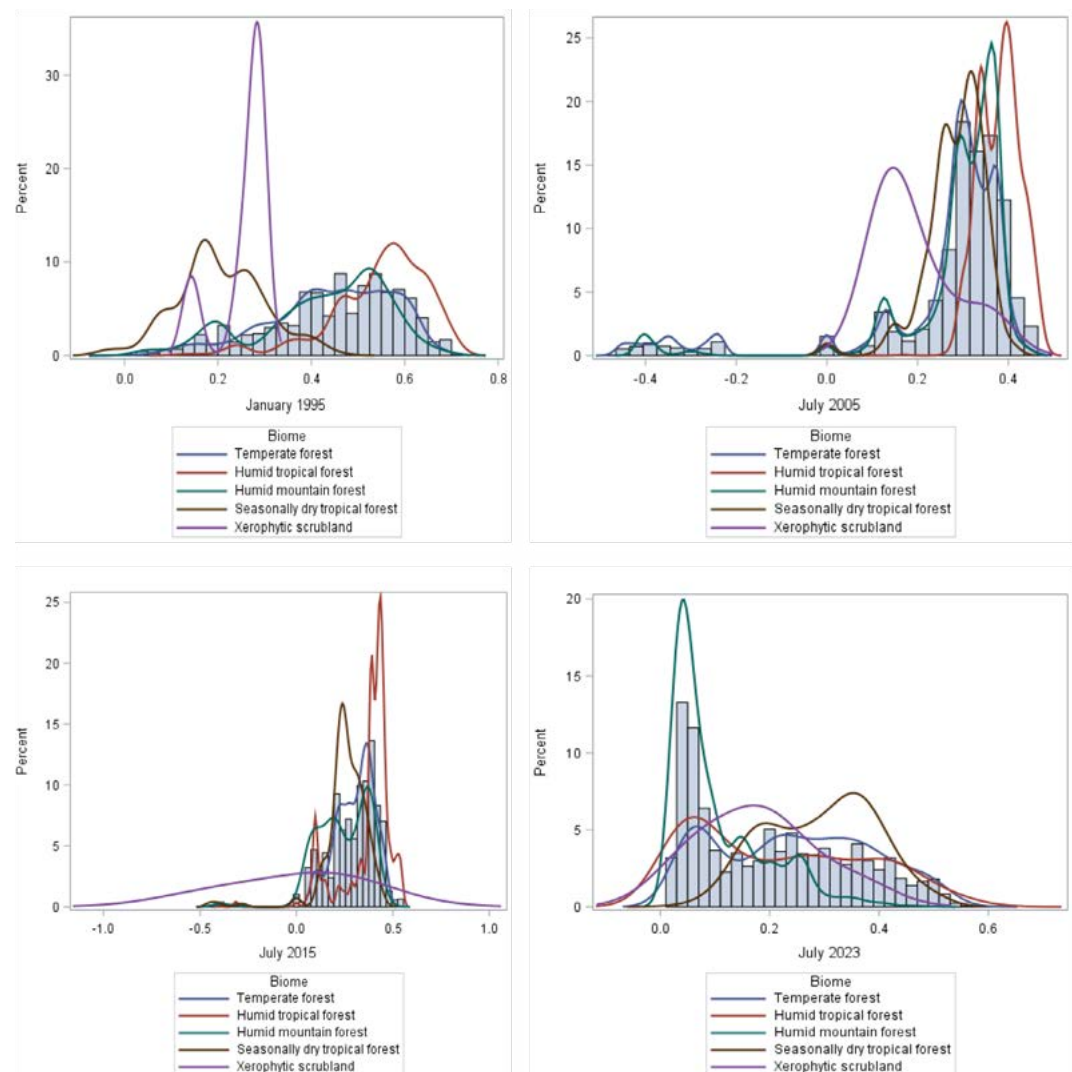


Figure 4. Normalized Difference Vegetation Index (NDVI) values for the biomes distributed in the District of Ixtlán, Oaxaca, Mexico, obtained through Kernel density analysis.

NDVI Density by Altitude

Altitudinal gradients play an important role in plant species distribution. NDVI values obtained in 1995 ranged from 0 to 0.8; in 2005, from -0.6 to 0.6 ; in 2015, from -0.5 to 0.6 ; and in 2023, from 0 to 0.6 , making vegetation degradation evident over time.

The highest altitudinal gradient showed mean NDVI values of 0.2, 0.4, and 0.58 in 1995; in 2005, this average decreased to 0.3; in 2015, the mean for this altitude was between 0.22 and 0.3; and in 2023, it was 0.1 (Figure 5).

Alpha diversity

The Dominance index indicates the probability that a single species completely dominates a biome; lower values reflect greater species richness, whereas values closer to 1 indicate lower species numbers (Medrano *et al.*, 2017). In this study, temperate forest and

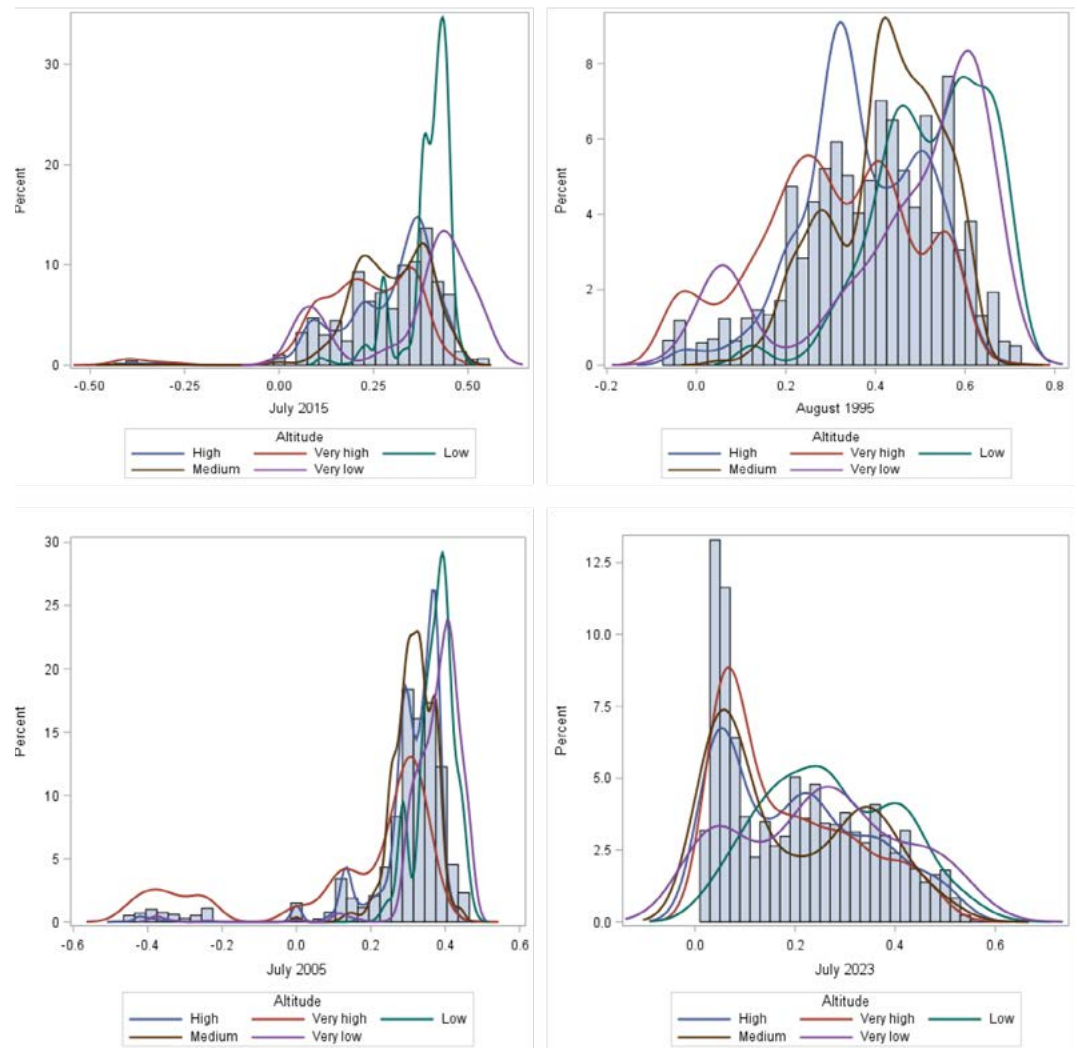


Figure 5. Normalized Difference Vegetation Index (NDVI) values by month and altitude obtained through Kernel density analysis.

mountain cloud forest exhibited the lowest dominance values (0.001377 and 0.001969, respectively). In contrast, xerophilous scrubland showed the highest dominance (0.1667), corresponding to only six recorded species. The Shannon index reflects species diversity. Values < 2 indicate low diversity, values between 2 and 3.5 indicate moderate diversity, and values > 3.5 are interpreted as high diversity (Carmona-Galindo & Carmona, 2013). Most biomes presented values greater than 3.5; temperate forest showed the highest value (6.58), whereas xerophilous scrubland had a value of 1.79, making it the least diverse (Figure 6). The Simpson index ranges from 0 to 1, with values closer to 1 indicating higher diversity and values near 0 reflecting dominance by one or few species (Simpson, 1949; Del Río *et al.*, 2003). Most biomes showed high diversity, with values close to 1 (mountain cloud forest=0.9; temperate forest=0.9). However, xerophilous scrubland presented the lowest diversity, consistent with its reduced species number (six species). The Menhinick index is a measure of species richness; higher values indicate greater richness. Temperate

forest recorded the highest value (26.94), followed by mountain cloud forest (22.54), while xerophilous scrubland showed the lowest value (2.45) (Figure 6).

Beta diversity

Beta diversity among biomes was calculated using the Whittaker index, which measures species turnover between communities. Values of zero in the matrix indicate no species turnover; however, species replacement was observed among several biome pairs.

The highest turnover values were recorded between xerophilous scrubland and the other biomes, particularly with mountain cloud forest (0.99) and seasonally dry tropical forest (0.99). In contrast, the lowest species replacement occurred between mountain cloud forest and temperate forest (0.50), as well as between mountain cloud forest and tropical humid forest (0.47246) (Table 3).

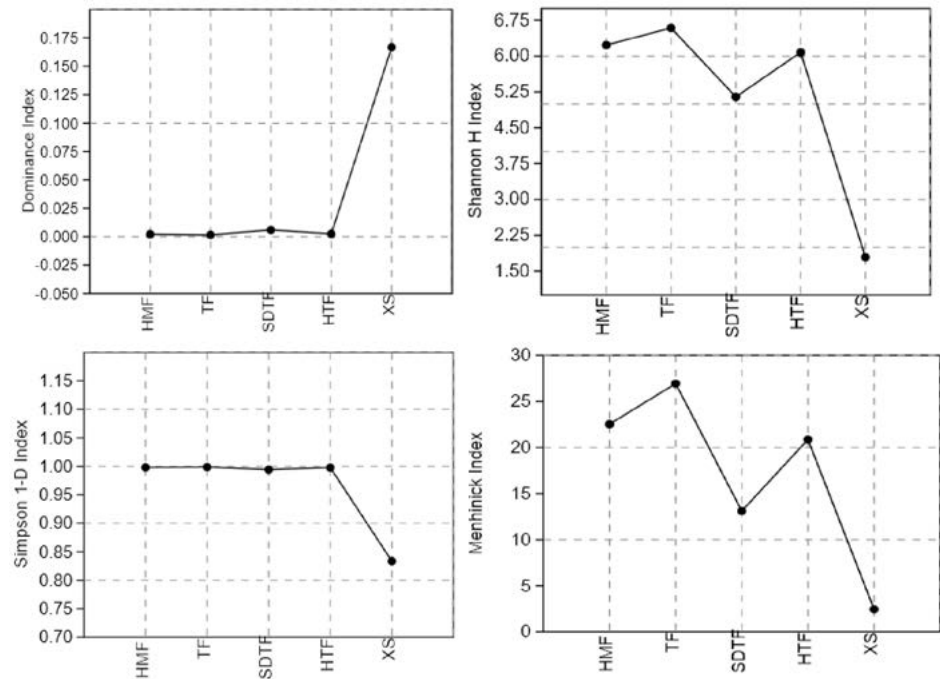


Figure 6. Diversity indices under biome-based analysis. A) Dominance index; B) Shannon index; C) Simpson index; D) Menhinick index; MCF=mountain cloud forest; TF=temperate forest; SDTF=seasonally dry tropical forest; THF=tropical humid forest; XS=xerophilous scrubland.

Table 3. Beta diversity values among biomes based on the Whittaker index.

	BHM	BTEMP	BTES	BTH	MXE
BHM	1				
BTEMP	0.50405	1			
BTES	0.82941	0.72829	1		
BTH	0.47246	0.65232	0.93421	1	
MXE	0.98833	0.98361	0.98876	0.99095	1

BHM=humid mountain forest, BTEMP=temperate forest; BTES=seasonally dry tropical forest; BTH=humid tropical forest; MXE=xerophytic scrubland.

Biome Similarity

The relationship between biomes and altitude, based on species presence, indicates that temperate forest and high altitude share more than 55% similarity. Likewise, tropical humid forest and low altitude show approximately 48% similarity, while mountain cloud forest and very high altitude present 45% similarity. A particular case is xerophilous scrubland, which shows 0% similarity. This may be attributed to its low species richness (only six species), making similarity with other biomes unlikely and suggesting that it represents a distinct biome (Figure 7). Additionally, a clustering trend was observed, forming two main groups. The first group comprises low altitudes associated with tropical humid forest, while the second includes medium, high, and very high altitudes grouped with mountain cloud forest and temperate forest. These two groups exhibit approximately 20% similarity. Finally, seasonally dry tropical forest shows only about 12% similarity with the two previously mentioned groups, likely due to its relatively lower species richness (172 species).

Regarding shrub presence across altitudinal levels, 228 species were recorded, in contrast to Bautista-Bello *et al.* (2019), who reported 132 species concentrated within the altitudinal range of 1957-3178 m. This differs from the findings of Mijango-Ramos *et al.* (2020), who suggest that species diversity decreases with increasing elevation due to less favorable climatic conditions (a decrease of 0.6 °C per 100 m in altitude). However, in the present case, greater species diversity was observed at higher elevations.

Vegetation vigor decreased over the years, as evidenced by the satellite imagery. These findings are consistent with Mamani and Román (2021), who reported a progressive decline in vegetation vigor over time. Additionally, they evaluated temperature and precipitation variables, identifying a relationship between increasing temperature, decreasing precipitation, and vegetation health. In contrast, Chambe *et al.* (2021) indicate that NDVI is more strongly influenced by temperature than by precipitation. Consequently, increasing temperature may promote vegetation development under more favorable environmental conditions, resulting in higher productivity and biomass accumulation.

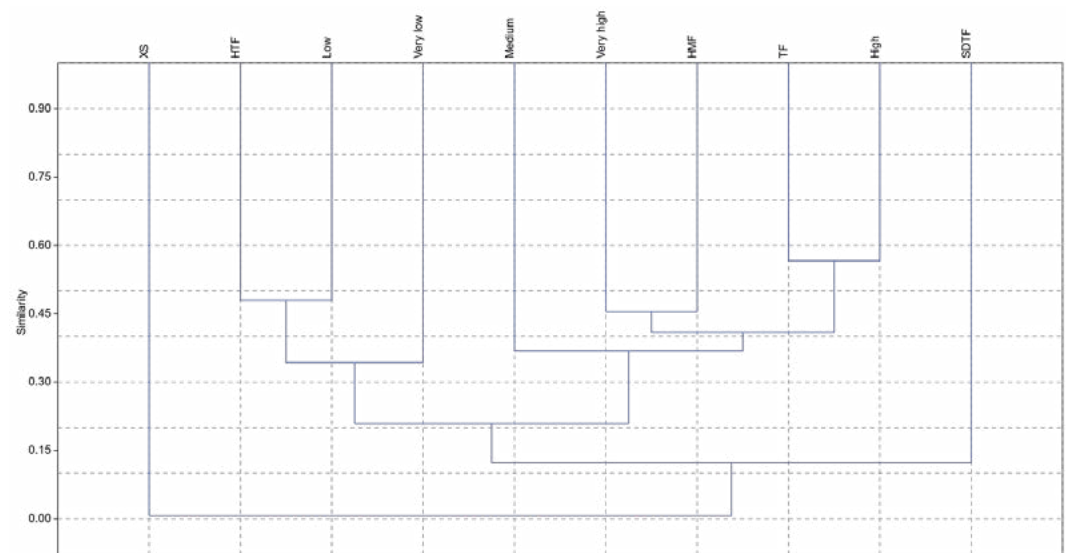


Figure 7. Similarity values between altitude and biome based on species presence, using the Jaccard index.

The images used in this study corresponded to multiple years and different seasons, in contrast to Ruiz *et al.* (2017), who employed only two images per year across four time periods. They assessed land-use and vegetation change, as well as the increase in human activities, and reported NDVI values ranging from 0.1 to 0.5 for xerophilous scrubland and oak forest. These values differ from those obtained in the present study, which range from -0.13 to 0.77 across the analyzed biomes, where higher altitudes exhibited lower NDVI values.

On the other hand, Olivares and López-Beltrán (2019) state that vegetation follows an annual cycle in response to regular rainfall patterns and soil water storage. Consistent with this, lower NDVI values were recorded during periods outside the rainy season, for example, in January 1995 and 2000, September 2010, and July 2023. Conversely, the highest values were recorded during the rainy season, specifically in July 2000 and November 2015 and 2023, in the Sierra Juárez of Ixtlán, Oaxaca.

Human activities affect ecosystem resilience, resulting in the loss, reduction, and delayed recovery of vegetation cover, as reported by Kafy *et al.* (2022). Remote sensing analysis based on NDVI shows the gradual deterioration of vegetation cover in the district of Ixtlán de Juárez. A similar effect was identified by Tuesta *et al.* (2023), who conducted a systematic review of multitemporal analyses using satellite imagery and found forest decline at the global level. However, in some Asian countries, they reported an increase in forested areas, possibly as a result of passive restoration processes. At the regional level, Suárez-Mota *et al.* (2023) evaluated the degree of ecological restoration at a university campus (UNSIJ) in the Sierra Norte of Oaxaca using satellite imagery and the Normalized Difference Vegetation Index. They found that arboreal vegetation and secondary vegetation increased by 10 to 24.6%, concluding that vegetation has shown notable improvement in area despite urban expansion within the university. At the state level, Gómez-Mendoza *et al.* (2008) analyzed variations in NDVI in the state of Oaxaca, southern Mexico. Using satellite information, they found that NDVI values during extremely dry periods were generally low, reflecting the predominant vegetation conditions of the state; however, analysis during the rainy season indicated rapid recovery of vegetation cover.

Seasonal analysis reflects dynamic NDVI values, as this index decreases during the dry season and increases during the rainy season within each year. However, when analyzed annually, NDVI shows a declining trend, indicating a loss of vegetation health. Barbosa *et al.* (2006), through satellite image analysis using the Normalized Difference Vegetation Index (NDVI), identified vegetation loss and deterioration across years and seasons. These findings are consistent with the results observed in the present study, as the changes in the Sierra Juárez, Oaxaca (Figure 3) are considerably evident.

Ecosystem degradation is a global concern, and various methods have been employed to assess this issue in specific areas. Currently, methodologies based on satellite imagery have been widely implemented, with NDVI being the most commonly used index to evaluate trends in ecosystem health, as noted by Gaitán *et al.* (2015).

As previously mentioned, in 1995 forest health was better than in the other evaluated years, with an average NDVI value of approximately 0.48. However, from 2005 onward, the highest average NDVI value recorded was 0.30. NDVI ranges vary depending on

the months analyzed, decreasing during the dry season and increasing during the rainy season. Nevertheless, the decline in vegetation health over the years has been evident: the highest NDVI levels were recorded in 1995 and the lowest in 2023, demonstrating limited ecosystem recovery (Figure 2).

Several biomes were evaluated, finding that the highest Shannon index values are presented by BTEM, BHM, and BTH, indicating that there is greater diversity than that evaluated by Dávila-Lara *et al.* (2019), mentioning that there is high diversity in forested areas; however, in areas with forest exploitation there is a tendency for dominance to exist, despite the fact that some temperate forest zones in the study were located within the analyzed area, they continue to be biomes with the presence of arboreal and shrub species.

REFERENCES

- Barbosa, H.A., Huete, A.R., & Baethgen, W.E. (2006). A 20-year study of NDVI variability over the Northeast Region of Brazil. *Journal of Arid Environments*, 67(2), 288-307. <https://doi.org/10.1016/j.jaridenv.2006.02.022>
- Baret, F., Guyot, G., & Major, D. J. (1989). TSAVI: A Vegetation index which minimizes soil brightness effects on LAI and APAR Estimation. 12th Canadian Symposium on Remote Sensing Geoscience and Remote Sensing Symposium, 3, 1355-1358. <https://doi.org/10.1109/IGARSS.1989.576128>
- Bautista-Bello, A.P., López-Acosta, J.C., Castillo-Campos, G., Gómez-Díaz, J. A., & Krömer, T. (2019). Diversidad de arbustos a lo largo de gradientes de elevación y perturbación en el centro de Veracruz, México. *Acta Botánica Mexicana*, 126, e1369. <https://doi.org/10.21829/abm126.2019.1369>
- Carmona-Galindo, V.D., & Carmona, T.V. (2013). La diversidad de los análisis de diversidad la diversidad de los analisis de diversidad. *Bioma*, 14(2), 20-28.
- Castellanos-Bolaños, J.F., Treviño-Garza, E.J., Aguirre-Calderón, O.A., Jiménez-Pérez, J., & Velázquez-Martínez, A. (2010). Diversidad arbórea y estructura espacial de bosques de pino-encino en Ixtlán de Juárez, Oaxaca. *Revista mexicana de ciencias forestales*, 1(2), 39-52. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S2007-11322010000200004&lng=es&nrm=iso&tlng=es
- Challenger, A. (1998). Utilización y conservación de los ecosistemas terrestres de México. pasado, presente y futuro. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad/ Instituto de Biología, UNAM/ Agrupación Sierra Madre. Ciudad de México: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad.
- Challenger, A. (2003). Conceptos generales acerca de los ecosistemas templados de montaña de México y su estado de conservación. En Sánchez, O., E. Vega, E. Peters y O. Monroy-Vilchis (eds.). Conservación de los ecosistemas templados de montaña en México, Instituto Nacional de Ecología. México, D.F., México. Pp. 17-44.
- Chambe, J., Quintana, D., & Sanga, M. (2021). Análisis multitemporal de la laguna Suches y del vigor de la vegetación del bofedal de Huaytire, Tacna. *Ciencias y Desarrollo*, 20(1), 27-39.
- CONABIO (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad). (2023). Sistema Nacional de Información sobre la Biodiversidad. Registros de ejemplares de plantas. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. <http://geoportal.conabio.gob.mx/#!plantas:1@m=satelite>
- Cortés-Castelán, J.C., & Islebe, G.A. (2005). Influencia de factores ambientales en la distribución de especies arbóreas en las selvas del sureste de México. *Revista de Biología tropical*, 53(1-2), 115-133. https://www.scielo.sa.cr/scielo.php?pid=S0034-77442005000100012&script=sci_arttext&tlng=en
- Cuyckens, G.A.E., Malizia, L.R., & Blundo, C. (2015). Composición, diversidad y estructura de comunidades de árboles en un gradiente altitudinal de selvas subtropicales de montaña (Serranías de Zapla, Jujuy, Argentina). *Madera y bosques*, 21(3), 137-148. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1405-04712015000300010&lng=es&tlng=es
- Dávila-Lara, M.A., Aguirre-Calderón, Ó.A., Jurado-Ybarra, E., Treviño-Garza, E., González-Tagle, M.A., & Trincado, G. (2019). Estructura y diversidad de especies arbóreas en bosques templados de San Luis Potosí, México. *Ecosistemas y Recursos Agropecuarios*, 6(18), 399-409. <https://doi.org/10.19136/era.a6n18.2112>
- Del Río, M., Montes, F., Cañellas, I., & Montero, G. (2003). Revisión: Índices de diversidad estructural en masas forestales. *Investigación agraria: Sistemas y Recursos Forestales*, 12(1), 159-176.

- Díaz, V., Sosa-Ramírez, J. & Pérez-Salicrup, D.R. (2012). Distribución y abundancia de las especies arbóreas y arbustivas en la Sierra Fría, Aguascalientes, México. *Polibotánica*, 34, 99-126. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1405-27682012000200004&lng=es&nrm=iso&tlng=es
- Fayech, D., & Tarhouni, J. (2021). Climate variability and its effect on normalized difference vegetation index (NDVI) using remote sensing in semi-arid area. *Modeling Earth Systems and Environment*, 7(3), 1667-1682. <https://doi.org/10.1007/s40808-020-00896-6>
- Gaitán, J.J., Donaldo Bran, D.E., & Azcona, C. (2015). Tendencia del NDVI en el período 2000-2014 como indicador de la degradación de tierras en Argentina: Ventajas y limitaciones. *Agriscientia*, 32(2), 83-93. http://www.scielo.org.ar/scielo.php?script=sci_abstract&pid=S1668-298X2015000200001&lng=es&nrm=iso&tlng=en
- García-García, S.A., Alanís-Rodríguez, E., Aguirre, C.Ó.A., Treviño-Garza, E.J., Cuéllar-Rodríguez, L.G., & Collantes, C.A. (2023). Composición, estructura y estado de la regeneración arbórea en un gradiente altitudinal en un bosque templado de Guadalupe y Calvo, Chihuahua. *Polibotánica* 56, 81-100. Doi: 10.18387/polibotanica.56.5
- Gomez-Mendoza, L., Galicia, L., Cuevas-Fernández, M.L., Magana, V., Gómez, G., & Palacio-Prieto, J.L. (2008). Assessing onset and length of greening period in six vegetation types in Oaxaca, Mexico, using NDVIprecipitation relationships. *International Journal Biometeorology*, 52, 511-520. doi:10.1007/s00484-008-0147-6
- Graciano-Ávila, G., Aguirre-Calderón, Ó.A., Alanís-Rodríguez, E., & Lujan-Soto, J.E. (2017). Composición, estructura y diversidad de especies arbóreas en un bosque templado del Noroeste de México. *Ecosistemas y recursos agropecuarios*, 4(12), 535-542. https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2007-90282017000300535
- Hammer, Ø., Harper, D.A.T., & Paul D.R. (2001). Past: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica*, 4, 4-9. http://palaeo-electronica.org/2001_1/past/issue1_01.htm
- Holguín-Estrada, V.A., Alanís-Rodríguez, E., Aguirre-Calderón, O., Yerena-Yamallel, J.I., & Pequeño-Ledezma, M.Á. (2021). Estructura y composición florística de un bosque de galería en un gradiente altitudinal en el noroeste de México. *Madera y bosques*, 27(2), e2722123. <https://doi.org/10.21829/myb.2021.2722123>
- Huang, S., Tang, L., Hupy, J.P., Wang, Y. & Shao, G. (2021). A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. *Journal of Forestry Research*, 32(1), 1-6. <https://doi.org/10.1007/s11676-020-01155-1>
- Huerta-Martínez, F.M., Briones, T.J.E., Neri, L.C., Muñoz, U.A., & Rosas, E.V.C. (2014). Relaciones entre comunidades arbóreas, suelo y el gradiente altitudinal en el volcán de Tequila, Jalisco. *Revista mexicana de ciencias forestales*, 5(24), 202-215. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2007-11322014000400015&lng=es&tlng=es
- INEGI (Instituto Nacional de Estadística y Geografía) (2021). Uso de suelo y vegetación, escala 1:250000, Serie VII (continuo nacional). Instituto Nacional de Estadística y Geografía. México.
- INEGI (Instituto Nacional de Estadística y Geografía) (2022). División política estatal 1:250000, 2022. Instituto Nacional de Estadística y Geografía. México.
- INEGI (Instituto Nacional de Estadística y Geografía) (2022). División política municipal 1:250000, 2022. Instituto Nacional de Estadística y Geografía. México.
- INEGI (Instituto Nacional de Estadística y Geografía), (2023). Modelos Digitales de Elevación de Alta Resolución LiDAR, Superficie ASCII, con resolución de 5m Oaxaca Escala 1:10000. Instituto Nacional de Estadística y Geografía. México.
- Abdulla-Al, K., Abdullah-Al, F., Abdullah-Al R., Md. Abdul, F., Zullyadini A. R., & Golam, S.S. (2022). Impact of vegetation cover loss on surface temperature and carbon emission in a fastest-growing city, Cumilla, Bangladesh. *Building and Environment*, 208, 108573. <https://doi.org/10.1016/j.buildenv.2021.108573>
- Ledo, A., Condés, S., & Montes, F. (2012). Revisión de índices de distribución espacial usados en inventarios forestales y su aplicación en bosques tropicales. *Revista Peruana de Biología*, 19(1), 113-124. http://www.scielo.org.pe/scielo.php?pid=S1727-99332012000100017&script=sci_arttext
- Li, S., Xu, L., Jing, Y., Yin, H., Li, X., & Guan, X. (2021). High-quality vegetation index product generation: A review of NDVI time series reconstruction techniques. *International Journal of Applied Earth Observation and Geoinformation*, 105, 102640. <https://doi.org/10.1016/j.jag.2021.102640>
- Llorente-Bousquets, J., & Morrone, J.J. (2001). Introducción a la biogeografía en Latinoamérica: Teorías, conceptos, métodos y aplicaciones. Facultad de Ciencias, UNAM, México.
- Mamani, V.A.J.P., & Román, A.C.R. (2021). Índice de vegetación y cambio climático: una evaluación multitemporal de imágenes landsat en la laguna paucarani en el periodo 1972 al 2018. *Ingeniería Investiga*, 3(2), 97-106. <https://doi.org/10.47796/ing.v3i2.535>

- Matas-Granados, L., Pizarro, M., Cayuela, L., Domingo, D., Gómez, D., & García, M.B. (2022). Long-term monitoring of NDVI changes by remote sensing to assess the vulnerability of threatened plants. *Biological Conservation*, 265, 109428. <https://doi.org/10.1016/j.biocon.2021.109428>
- Mazzola, M.B., Kin, A.G., Morici, E.F., Babinec, F.J., & Tamborini, G. (2008). Efecto del gradiente altitudinal sobre la vegetación de las sierras de Lihue Calel (La Pampa, Argentina). *Boletín de la Sociedad Argentina de Botánica*, 43, 103-109. https://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S1851-23722008000100008&lng=es&tlng=en
- Medrano, M.M. de J., Hernández, F.J., Corral, R.S., & Nájera, L.J.A. (2017). Diversidad arbórea a diferentes niveles de altitud en la región de El Salto, Durango. *Revista mexicana de ciencias forestales*, 8(40), 57-68. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2007-11322017000200057&lng=es&tlng=es
- Mijango-Ramos, Z., Sánchez, M., Vergara, C., & Mendieta, J. (2020). Diversidad de árboles y arbustos en la reserva privada cerro chucantí en Darién, Panamá. *Tecnociencia*, 22(1), 17-31. <http://portal.amelica.org/ameli/jatsRepo/224/2241124002/index.html>
- Olivares, B.O., & López-Beltrán, M.A. (2019). Índice de vegetación de diferencia normalizada aplicado al territorio indígena agrícola de Kashaama, Venezuela. *Cuadernos de Investigación UNED*, 11(2), 112-121. <https://dx.doi.org/10.22458/urj.v11i2.2299>
- Pesaresi, S., Mancini, A., & Casavecchia, S. (2020). Recognition and characterization of forest plant communities through Remote-Sensing NDVI time series. *Diversity*, 12(8), 8. <https://doi.org/10.3390/d12080313>
- QGIS Development Team (2019) Geographic Information System, version 3.4.8. QGIS Association. <http://www.qgis.org>
- Ruiz, D.M.E., Orozco, H.M.E., Granados, R.R., & Álvarez, A.G. (2017). Cambio de uso del suelo e Índice de vegetación de Diferencia Normalizada (NDVI), subcuenca del río Salado, México. *GeoSIG*. 9, 39-50.
- Ruiz-Aquino, F., Valdez-Hernández, J. I., Romero-Manzanares, A., Manzano-Méndez, F., & Fuentes-López, M.E. (2015). Distribución espacial de dos especies de encinos y atributos ecológicos del bosque de pino-encino en Ixtlán de Juárez, Oaxaca. *Revista Chapingo. Serie ciencias forestales y del ambiente*, 21(1), 67-80. <https://www.scielo.org.mx/pdf/rcsfa/v21n1/v21n1a6.pdf>
- Rzedowski, J. (1978). Vegetación de México. Limusa. México, D.F.
- SAS Institute Inc. (2013). Statistical Analysis System, versión 4. Cary, NC, USA: Author.
- Sánchez, O., Vega, E., Peters, E., & Monroy, V.O. (2003). Conservación de ecosistemas templados de montaña en México. Instituto Nacional de Ecología-Secretaría de Medio Ambiente y Recursos Naturales. México, D.F., México. 315 pp.
- Sánchez-Díaz, B. (2018). La teledetección en investigaciones ecológicas como apoyo a la conservación de la biodiversidad: Una revisión. *Revista científica*, 33, 243-253. <https://doi.org/10.14483/23448350.13370>
- Sánchez-Gutiérrez, F., Valdez-Hernández, J.I., Hernández-de la Rosa, P., & Beltrán-Rodríguez, L. (2019). Distribución y correlación espacial de especies arbóreas por gradiente altitudinal en la Selva Lacandona, Chiapas. *Revista mexicana de ciencias forestales*, 10(54), 74-99. <https://doi.org/10.29298/rmcf.v10i54.590>
- SERMARNAT (Secretaría de Medio Ambiente y Recursos Naturales), (2018). Sistema Nacional de Información sobre Biodiversidad de México. Gobierno de México. <https://www.gob.mx/semarnat/articulos/sistema-nacional-de-informacion-sobre-biodiversidad-de-mexico-153983#:~:text=Con%20este%20fin%20se%20cre%C3%B3,gesti%C3%B3n%20de%20su%20capital%20natural>
- Simpson, E.H. (1949). Measurement of Diversity. *Nature*, 163, 688.
- Suárez-Mota, M.E. & Villaseñor, J.L. (2011). Las compuestas endémicas de Oaxaca, Mexico: diversidad y distribución. *Boletín de la Sociedad Botánica de México*, 88, 55-66.
- Suárez-Mota, M.E., Bautista-Juárez, I., Juárez-Muñoz, A.M., & Villaseñor, J.L. (2023). Campus universitarios como unidades de restauración ecológica: el caso de la Universidad de la Sierra Juárez, Oaxaca, México. *Ecosistemas*, 32(2), 1-18. <https://doi.org/10.7818/ECOS.2517>
- Tamayo, J.L. (1990). Geografía moderna de México. Trillas. México, D. F., México. 512 pp.
- Torres, R.S.S., Arturi, M.F., Contreras, C., Peter, G., & Zeberio, J.M. (2015). Variaciones geográficas de la estructura y composición de la vegetación leñosa en el límite entre el espinal y el monte en el Noreste de la Patagonia (Argentina). *Boletín de la Sociedad Argentina de Botánica*, 50(2), 209-215. http://www.scielo.org.ar/scielo.php?script=sci_abstract&pid=S1851-23722015000200007&lng=es&nrm=iso&tlng=es
- Tuesta, R.H.P., Oliver, J.A.I., & Inga, M.E.R. (2023). Una revisión del uso de imágenes Sentinel-2 para el monitoreo de la cobertura boscosa a nivel global. *Ingeniería y Competitividad*, 25(3), 3. <https://doi.org/10.25100/iyc.v25i3.12708>
- USGS. (2023). Satélite Landsat 5, 7 y 8. USGS science for a changing world. <https://earthexplorer.usgs.gov/>

- Valois-Cuesta, H., Córdoba-Arias, J.A., & Rentería-Arriaga, E. (2016). Patrones de diversidad de plantas en un gradiente de baja elevación en el Chocó, Colombia, usando especies indicadoras (Rubiaceae). *Revista Mexicana de Biodiversidad*, 87(4), 1275-1282. <https://doi.org/10.1016/j.rmb.2016.10.001>
- Villaseñor, J. & Ortiz, E. (2014). Biodiversidad de las plantas con flores (División Magnoliophyta) en México. *Revista de Biodiversidad Mexicana*, 85, 134-142.
- Zacarías-Eslava, Y., & Del Castillo, R.F. (2010). Comunidades vegetales templadas de la Sierra Juárez, Oaxaca: pisos altitudinales y sus posibles implicaciones ante el cambio climático. *Boletín de la Sociedad Botánica de México*, 87, 13-28. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0366-21282010000200002&lng=es&tlng=es
- Zhu, W., Lv, A., & Jia, S. (2011). Spatial distribution of vegetation and the influencing factors in Qaidam Basin based on NDVI. *Journal of Arid Land*, 3, 85-93. <https://doi.org/10.3724/SPJ.1227.2011.00085>



Analysis of the Physicochemical Properties of “La Encantada” Lagoon During the Rainy Season in Lagunas de Montebello National Park, Chiapas

González-Espinosa, Rubí¹; Pérez-Hernández, Omar¹; Castañón-González, José¹; Trejo-Paniagua, Blanca¹; Rosales-Quintero, Arnulfo^{1*}

¹ Tecnológico Nacional de México, Campus Tuxtla Gutiérrez. Carretera Panamericana Km. 1080, Tuxtla Gutiérrez, Chiapas, México, C.P. 29050.

* Correspondence: arquinte@tuxtla.tecnm.mx

ABSTRACT

Objective: To comprehensively evaluate the physicochemical characteristics of “La Encantada” Lagoon, located within Lagunas de Montebello National Park (PNLM), during the 2024 rainy season.

Design/methodology/approach: Three sampling points (A, B and C) were established within the lagoon at depths of 15-30 cm, with three replicates per site. In situ measurements included pH, temperature, and electrical conductivity (EC), as well as turbidity, apparent color, and total suspended solids (TSS). Samples were preserved at 4 °C and subsequently reanalyzed ex situ to ensure analytical quality control and measurement consistency.

Results: *In situ* measurements showed turbidity values ranging from 18-19 FAU and TSS from 16-18 mg L⁻¹, with low spatial variability across the lagoon. EC exhibited spatial heterogeneity, with lower values at site A (226 $\mu\text{S cm}^{-1}$) compared to sites B-C (303-305 $\mu\text{S cm}^{-1}$). Apparent color ranged from 111 Pt-Co (A) to 136 Pt-Co (B). *Ex situ* analyses recorded slightly higher temperatures (26.2-26.5 °C) and stable alkaline pH values (9.16-9.40). EC increased to 307-312 $\mu\text{S cm}^{-1}$, while turbidity ranged from 14-21 FAU and apparent color from 105-129 Pt-Co. TSS concentrations varied between 11-17 mg L⁻¹.

Study limitations/implications: These findings establish a scientific baseline for assessing the interactions among hydrometeorological drivers, water quality parameters, and microalgal community dynamics within PNLM.

Findings/conclusions: The results indicate that the lagoon exhibits persistent alkaline conditions and reduced optical water quality during the rainy season. This environmental setting promotes eutrophication processes and potential alterations in trophic structure, consistent with reported occurrences of microalgal proliferation in “La Encantada” Lagoon. Furthermore, these findings establish a scientific baseline for assessing the interactions among hydrometeorological drivers, water quality parameters, and microalgal community dynamics within PNLM.

Citation: González-Espinosa, R., Pérez-Hernández, O., Castañón-González, J., Trejo-Paniagua, B., & Rosales-Quintero, A. (2026). Analysis of the Physicochemical Properties of “La Encantada” Lagoon During the Rainy Season in Lagunas de Montebello National Park, Chiapas. *Agro Productividad*. <https://doi.org/10.32854/047tav98>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: October 9, 2025.

Accepted: January 15, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 233-241.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Lagunas de Montebello National Park (PNLM), located in southeastern Chiapas, Mexico, was officially designated as a national park in 1959 (CONANP, 2025). In 2003, it was recognized as Ramsar Site No. 1325 due to its ecological significance as a complex

of permanent and seasonal karst freshwater wetlands characterized by high biodiversity value (Ramsar, 2025). Since 2009, PNLM has been incorporated into UNESCO's World Network of Biosphere Reserves under the Man and the Biosphere (MAB) Programme. The protected area harbors more than 2,315 recorded species of flora and fauna, of which 185 are classified under some conservation risk category (UNESCO, 2025).

PNLM is a federally protected area encompassing 6,286.83 hectares distributed between the municipalities of La Trinitaria and La Independencia (CEIEG, 2025). The park is physiographically structured into two principal regions: a northwestern plateau and a southeastern intermontane zone. Within this karst landscape, more than 50 lakes of karstic origin are present, exhibiting distinctive color gradients ranging from emerald green to turquoise blue. These optical characteristics are primarily associated with carbonate dissolution processes, soil stratification, aquatic vegetation dynamics, and solar light refraction effects.

The lakes have been classified into four morphometric categories: (1) large and deep; (2) large and shallow; (3) small and deep; and (4) small and shallow. Plateau-region lakes are predominantly sustained by groundwater discharge and surface runoff from the Río Grande de Comitán (RGC), which forms part of Mexico's National Hydrological Region No. 30 Grijalva-Usumacinta (Sosa-Aranda & Zambrano, 2019; Caballero *et al.*, 2025a). Notably, seven lakes constitute the Tepancoapan System: San Lorenzo, Bosque Azul, Peninsular, Esmeralda, Bartolo, Peñasquito, and Encantada. During the rainy season, these lakes become seasonally interconnected through overflow and flooding of adjacent lowlands, forming a single hydrologically continuous water body (CONANP, 2019).

The National Commission of Natural Protected Areas (CONANP) has reported that since 2002, this lacustrine system has exhibited noticeable changes in lagoon coloration, as well as episodes of aquatic fauna mortality (CONANP, 2019). In January 2003, the National Water Commission (CONAGUA), in collaboration with the National Council of Science and Technology (CONACyT), initiated a systematic monitoring program during both the rainy and dry seasons to investigate the variations in water coloration documented in at least four lagoons within the protected area. The monitoring strategy included comparative analyses between lakes exhibiting oligotrophic characteristics and those showing signs of eutrophication, with the objective of identifying shifts in water quality and their relationship with ecosystem dynamics. However, in recent years, environmental deterioration has intensified progressively, potentially associated with wastewater discharge, excessive agrochemical use, and deforestation in the surrounding watershed (Maya-García, 2017; Sosa-Aranda & Zambrano, 2019; Vargas-Sánchez *et al.*, 2022).

Previous studies have addressed specific components of the ecological dynamics within PNLM. Morales-Hernández *et al.* (2023) documented the presence of microalgal taxa such as *Monoraphidium* sp. and *Navicula* sp. in "La Encantada" Lagoon, and reported their association with key water quality indicators, including chemical oxygen demand (COD), biochemical oxygen demand (BOD), and chlorophyll concentrations.

Within this context, the present study assesses "La Encantada" Lagoon during the 2024 rainy season, aiming to characterize representative physicochemical parameters, evaluate their relationship with aquatic biodiversity and water quality status, and examine

their potential linkage with precipitation patterns and anthropogenic pressures in the surrounding watershed.

MATERIALS AND METHODS

Study Area

“La Encantada” Lagoon is located at 16° 07' N latitude and 91° 43' W longitude (Figure 1), at an elevation ranging between 1,467 and 1,492 m above sea level within Lagunas de Montebello National Park (PNLM), Chiapas, Mexico. The region is characterized by a warm subhumid to semi-warm climate with rainfall distributed throughout the year, a mean annual precipitation of approximately 1,800 mm, and a mean annual temperature of 17 °C (Mora *et al.*, 2017).

Sampling and Collection

Fieldwork was conducted from October 7 to October 9, 2024, during the rainy season. Three sampling points were established within the lagoon, and water samples were collected at depths between 15 and 30 cm using sterilized polyethylene containers. Three replicates were obtained at each sampling site according to the geographic coordinates detailed in Table 1 and illustrated in Figure 2.

During transport, samples were maintained at 4 °C in compliance with the specifications established by NOM-230-SSA1-2002 to preserve sample integrity and minimize physicochemical alterations prior to laboratory analysis.

Physicochemical Characterization

In Situ Measurements

The analyzed parameters included pH, temperature, and electrical conductivity (EC), measured using a portable HQ40D multiparameter meter (Hach®, USA) in accordance with the manufacturer’s specifications. Turbidity (FAU), apparent color (Pt-Co), and total



Figure 1. Location of the study area and boundary polygon of PNLM (adapted from Google Maps, 2025a).



Figure 2. Sampling points in “La Encantada” Lake; geographic coordinates are presented in Table 1 (adapted from Google Maps, 2025b).

Table 1. Geographic coordinates of the sampling points in “La Encantada” Lagoon.

Lagoon	Sampling Points	Latitude (N)	Longitude (O)
La Encantada	A	16° 7' 13.5"	91° 43' 49.6"
	B	16° 7' 10.1"	91° 43' 40.6"
	C	16° 7' 18.9"	91° 43' 42.9"

suspended solids (TSS, mg L^{-1}) were determined using a DR900 portable colorimeter (Hach[®], USA).

Ex Situ Measurements

Parameters initially measured in situ were subsequently reanalyzed ex situ at Laboratory No. 9 of Polo Tecnológico at the Instituto Tecnológico de Tuxtla Gutiérrez to verify measurement consistency and detect potential variations associated with sample transport and handling. This procedure constituted an essential quality control step to ensure data reliability and analytical reproducibility.

The physicochemical characterization of the lagoon was established as a preliminary and necessary stage for subsequent microalgal isolation, given that water quality conditions directly influence microalgal diversity, abundance, and physiological status.

RESULTS AND DISCUSSION

During the rainy season, the mean water temperature across the three sampling sites was 21 ± 2 °C, with an alkaline pH of 9 ± 1 . Turbidity averaged 18 ± 1 FAU, and TSS remained at 16 ± 2 mg L^{-1} , representing the parameters with the lowest spatial variability among in situ measurements. In contrast, EC exhibited pronounced differences among sampling sites, with the lowest value recorded at site A ($226 \mu\text{S cm}^{-1}$) and the highest at site

C ($305 \mu\text{S cm}^{-1}$). Apparent color showed a similar spatial pattern, with site B presenting the highest value (136 Pt-Co) and site A the lowest (111 Pt-Co) (Table 2).

These variations likely reflect differences in mineralization gradients and suspended particulate composition among the evaluated zones, potentially associated with localized hydrological inputs and internal biogeochemical processes within the lagoon.

During the *ex situ* verification conducted in the rainy season, the mean water temperature across the three sampling sites was 26.3 ± 0.15 °C, showing higher values than those obtained *in situ*. The pH remained within an alkaline range (9.31 ± 0.12), with minimal variation among sampling points. Turbidity averaged 17 ± 3.6 FAU, while total suspended solids (TSS) ranged between 11 and 17 mg L^{-1} , exhibiting moderate variability.

In contrast, electrical conductivity exhibited higher values than those recorded *in situ*, ranging from $307 \mu\text{S cm}^{-1}$ at site B to $312 \mu\text{S cm}^{-1}$ at site A. Apparent color followed a similar pattern, with the highest value observed at site C (129 Pt-Co) and the lowest at site A (105 Pt-Co) (Table 3). These discrepancies relative to *in situ* measurements may reflect minor physicochemical alterations during sample transport and handling, without compromising the analytical reliability of the dataset for water quality assessment.

DISCUSSION

During the rainy season, “La Encantada” Lagoon exhibited significant variations in its physicochemical parameters, reflecting the influence of precipitation patterns and potential anthropogenic inputs.

Water Temperature

During the rainy season, *in situ* water temperature remained within the typical range reported for shallow subtropical water bodies. However, once the samples were transported

Table 2. Mean values of the physicochemical parameters measured *in situ*.

Parameter	Point A1-A3	Point B1-B3	Point C1-C3
T	21.9 °C	22.7 °C	23.9 °C
pH	9.14	9.61	9.65
EC	$226 \mu\text{S cm}^{-1}$	$303 \mu\text{S cm}^{-1}$	$305 \mu\text{S cm}^{-1}$
Turbidity	19 FAU	19 FAU	18 FAU
Color	111 Pt-Co	136 Pt-Co	132 Pt-Co
TSS	16 mg L^{-1}	18 mg L^{-1}	16 mg L^{-1}

Table 3. Mean values of the physicochemical parameters determined *ex situ*.

Parameter	Point A1-A3	Point B1-B3	Point C1-C3
T	26.2 °C	26.5 °C	26.3 °C
pH	9.16	9.4	9.37
EC	$312 \mu\text{S cm}^{-1}$	$307 \mu\text{S cm}^{-1}$	$310 \mu\text{S cm}^{-1}$
Turbidity	16 FAU	21 FAU	14 FAU
Color	105 Pt-Co	116 Pt-Co	129 Pt-Co
TSS	11 mg L^{-1}	17 mg L^{-1}	16 mg L^{-1}

for laboratory verification, temperature values increased. This discrepancy between *in situ* and *ex situ* measurements is expected, as post-collection warming or cooling during handling and transport may influence recorded values.

Water temperature is closely linked to seasonal climatic conditions. Rainfall events are commonly associated with increased cloud cover and the inflow of relatively cooler surface waters, which may slightly reduce lagoon temperature. From an ecological perspective, temperature constitutes a key driver of physical, chemical, and biological processes in aquatic systems. Xu *et al.* (2022) highlight that water temperature plays a critical role in regulating lake primary productivity by influencing physical properties, chemical reaction rates, and biological activity, including microalgal growth.

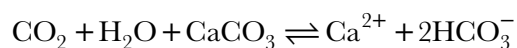
Similarly, Zeng *et al.* (2022) indicate that temperature significantly affects water column stratification. In shallow systems such as “La Encantada” Lagoon, intense rainfall events may disrupt thermal stratification through the input of cooler water masses and wind-induced mixing, thereby preventing the establishment of stable thermal layers. This process enhances vertical mixing of nutrients and dissolved oxygen throughout the water column, although it may also promote the resuspension of colder bottom sediments.

An important consideration is that persistently warm and stable temperature conditions can favor certain algal proliferations. At a global scale, twentieth-century warming has been associated with an increased frequency of harmful algal blooms (HABs), closely linked to rising water temperatures. Although water temperature in “La Encantada” during the rainy season is not elevated, any sustained thermal increase could promote the proliferation of opportunistic microalgae, which typically thrive under warmer conditions.

Water pH

Water pH remained slightly alkaline under both *in situ* and *ex situ* conditions during the rainy season. This condition is primarily attributable to the presence of carbonate species in the water column, which are characteristic of karst regions and areas influenced by calcareous groundwater infiltration and/or intense photosynthetic activity. PNLM is located within one of the most diverse karst regions in Mexico (Mora *et al.*, 2016), where tropical, rainforest, and warm subhumid karst systems are well represented within the protected area.

In karstic lakes, water circulation promotes interaction with carbonate bedrock (limestone and dolomite), and the geochemical equilibrium is largely governed by the carbonate system:



Calcite and dolomite dissolution, driven by soil-derived CO_2 and microbial respiration, enriches the water with bicarbonate and calcium ions, conferring high buffering capacity and typically maintaining pH values above 7.5. This represents a defining feature of karst systems, characterized by elevated dissolved inorganic carbon (DIC), increased $\text{Ca}^{2+}/\text{Mg}^{2+}$ concentrations, and dominance of the $\text{HCO}_3^-/\text{CO}_3^{2-}$ pair in carbonate chemistry.

In neotropical karst lakes, reported pH values range from approximately 7.4 to 9.2, with total dissolved solids (TDS) generally $\leq 500 \text{ mg L}^{-1}$, which is consistent with the ~ 9 pH observed during the rainy season in “La Encantada” Lagoon (Chen *et al.*, 2021; Caballero *et al.*, 2025).

Electrical Conductivity

EC is an indicator of dissolved ionic content and total salinity within the lagoon. During the rainy season, EC values measured in “La Encantada” suggest a moderate ionic load in the water column. Studies conducted in comparable lacustrine systems indicate that rainfall generally reduces conductivity through dilution effects, as precipitation typically exhibits low ionic strength ($< 50 \mu\text{S cm}^{-1}$). However, this dilution effect may be offset or even reversed when surface runoff mobilizes minerals and anthropogenic contaminants from the watershed into the aquatic system (Kondowe *et al.*, 2022).

Notably, the EC values recorded during the 2025 rainy season were lower than those reported by Morales-Hernández *et al.* (2023), who documented a mean EC of $370 \mu\text{S cm}^{-1}$. Although sampling sites differed between studies, the comparatively lower EC observed in the present assessment may reflect enhanced dilution of ionic constituents during rainfall events, potentially reducing overall ionic concentration in the lagoon.

Water Clarity-Related Parameters

Turbidity is an optical measure of the loss of water clarity caused by suspended particles—both inorganic and organic, including phytoplankton—that scatter and/or attenuate light. In freshwater systems, turbidity is closely associated with light attenuation, photic zone depth, and overall water transparency (USGS, 2018; Bowers *et al.*, 2020). The *in situ* turbidity values recorded in “La Encantada” (~ 18 -19 FAU) and the *ex situ* range (~ 14 -21 FAU) indicate a moderately turbid state consistent with rainy-season conditions. These levels suggest sufficient particulate matter to reduce transparency and light penetration, although not reaching extreme turbidity thresholds.

Precipitation events typically involve two common phases: (i) an initial dilution stage, characterized by low-salinity meteoric inputs that may temporarily reduce turbidity, and (ii) a subsequent increase due to surface runoff transporting fine sediments and organic detritus into the water body. It has been documented that a single storm event can double turbidity within less than 36 hours, and that seasonal mean turbidity during wet periods is generally elevated due to diffuse inputs and sediment resuspension (Bowers *et al.*, 2020; Umwali *et al.*, 2021). In shallow lakes, wave action and inflow pulses further promote bottom sediment resuspension, sustaining turbidity levels even after peak rainfall has subsided (Wymore *et al.*, 2019).

Apparent color values (~ 105 -136 Pt-Co; also referred to as APHA/Hazen units) reflect the presence of chromophoric dissolved organic matter (CDOM). The observed coloration range is likely attributable to rainfall-driven mobilization of CDOM from soils, leaf litter, and organic-rich substrates within the watershed. CDOM strongly absorbs blue and ultraviolet wavelengths, imparting a yellowish-brown coloration to the water and reducing both euphotic zone depth and spectral light quality. This selective

attenuation—particularly reduced blue/UV availability— can limit primary productivity and influence phytoplankton community composition, even under comparable turbidity conditions (Ahonen *et al.*, 2024; Younes & Berggren, 2024).

During the wet season, total suspended solids (TSS) typically increase due to watershed erosion, surface runoff (clays, silts, vegetal detritus), and internal sediment resuspension. In tropical floodplain lakes and shallow lentic systems, TSS often exhibit pronounced rainy-season peaks, regulating the pulsed transport of particulate nutrients between hydrological compartments (river-lake connectivity) and influencing overall ecosystem functioning.

CONCLUSIONS

“La Encantada” Lagoon, located within PNLM, exhibits alkaline conditions during the rainy season, consistent with its karstic geochemical setting and carbonate buffering dynamics. Reduced optical water quality—evidenced by moderate turbidity and elevated apparent color— is linked to diffuse watershed inputs and spatial ionic heterogeneity associated with rainfall and surface runoff dynamics. This environmental scenario may promote eutrophication processes and shifts in trophic structure, potentially favoring increased microalgal dominance under sustained climatic or anthropogenic pressures.

Accordingly, seasonal and event-based monitoring is recommended to better characterize short-term physicochemical variability and long-term ecological trends within the lagoon.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Tecnológico Nacional de México (TecNM) under Project No. 20337.24-P, entitled “Evaluación del potencial ficorremediador de microalgas aisladas de una laguna del Parque Nacional Lagunas de Montebello.” RGE also acknowledges SECIHTI for the postgraduate scholarship (CVU: 1347140).

REFERENCES

- Ramsar. Parque Nacional Lagunas de Montebello|Servicio de Información de Sitios Ramsar. Available: <https://rsis.ramsar.org/ris/1325>
- CONANP, Comisión Nacional de Áreas Naturales Protegidas. Lagunas de Montebello.2025. <https://simec.conanp.gob.mx/ficha.php?anp=167>.
- UNESCO. Lagunas de Montebello - Man and the Biosphere Programme (MAB). Available: <https://www.unesco.org/en/mab/Lagunas-de-montebello>.
- Gobierno de Chiapas. Perfiles Municipales. Available: <https://www.ceieg.chiapas.gob.mx/perfiles/Inicio>
- Sosa-Aranda I, Zambrano L. 2019. Relationship between turbidity and the benthic community in the preserved Montebello Lakes in Chiapas, Mexico,” *Mar. Freshw. Res.*, vol. 71, no. 7, pp. 824-831. doi: 10.1071/mf19090.
- Caballero M, Waters MN, Amezcua M, Ruiz-Fernández AC, Sigala I, Alcocer J. 2025a. Recent human-induced ecological changes in a Neotropical karst lake of southern México. *CATENA*, vol. 256, 109-119. doi: 10.1016/j.catena.109119.
- CONANP, 2019. <https://www.gob.mx/conanp/documentos/parque-nacional-lagunas-de-montebello-209454>.
- Maya-García EE. 2017. Estimación del estado trófico de 18 lagos del Parque Nacional “Lagunas de Montebello”, Chiapas, México. Tesis de licenciatura, UNAM, <https://tesiumamdocumentos.dgb.unam.mx/ptd2017/junio/0760080/0760080.pdf>.
- Vargas-Sánchez M, Alcocer J, Oseguera LA. 2022. Seston and eutrophication on a tropical karst lake district: Lagunas de Montebello, Chiapas, Mexico, *Limnetica*, vol. 41, no. 2, pp. 269-279. doi: 10.23818limn.41.16.

- Morales-Hernández SM, Robles-González GR, González-Díaz AA, Rosales-Quintero A, Ruiz-Valdiviezo VM, Castañón-González JH. 2022. Bioindicator organisms of the environmental impact in the Montebello lagoons, Chiapas, Mexico, *J. Bioeng. Biomed. Res.*, vol. 6, no. 2, pp. 65-71.
- Mora, Boletín de la Sociedad Geológica Mexicana, *Bol. Soc. Geol. Mex.*, vol. 68, pp. 377-394, 2016. Available: <http://www.igeograf.unam.mx/sigg/>
- Google Maps. 2025a. Ubicación de laguna “Bosque Azul” y “La Encantada” del Parque Nacional Lagunas de Montebello, Accedido en octubre 02, 2025. (https://www.google.com/maps/@16.1248146,-91.7341514,2320m/data=!3m1!1e3?entry=tu&g_ep=EgoyMDI1MTAwMS4wIKXMDSoASAFQAw3D%3D).
- Google Maps. 2025b. Ubicación de laguna “La Encantada” del Parque Nacional Lagunas de Montebello, Accedido en octubre 2025. (https://www.google.com/maps/@16.1203262,-91.7281297,439m/data=!3m1!1e3?entry=tu&g_ep=EgoyMDI1MTAwMS4wIKXMDSoASAFQAw%3D%3D).
- Xu W, Duan L, Wen X, Li H, Li D, Zhang Y, Zhang HW. 2022. Effects of Seasonal Variation on Water Quality Parameters and Eutrophication in Lake Yangzong, *Water*, vol. 14, no. 17, 2732. doi: 10.3390/w14172732.
- Zeng Y, Chang F, Wen X, Duan L, Zhang Y, Liu Q, Zhang H. 2022. Seasonal Variation in the Water Quality and Eutrophication of Lake Xingyun in Southwestern China, *Water*, vol. 14, no. 22, 3677. doi: 10.3390/w14223677.
- Chen W, Huang H, Li H, Cao J, Li Q, Chen Y, Bai B, Zeng H. 2021. Coupled nitrogen transformation and carbon sink in the karst aquatic system: a review,” *Blue-Green Systems*, vol. 3, no. 1, 201-212. doi: 10.2166/bgs.2021.120.
- Caballero M, Vázquez G, Ruiz-Fernández AC, Alcocer J, Mora-Palomino LM. 2025a. Diatom diversity and distribution in Neotropical karst lakes under anthropogenic stress. *PLOS ONE*, vol. 20, no. 7. doi: 10.1371/journal.pone.0327201.
- Kondowe BM, Masese FO, Raburu PO, Singini W, Sitati A, Walumona RJ. 2022. Seasonality in Environmental Conditions Drive Variation in Plankton Communities in a Shallow Tropical Lake, *Front. Water*, vol. 4, 883-767, 2022. doi:10.3389/frwa.2022.883767.
- Bowers DG, Roberts EM, Hogue AM, Fall KA, Massey GM, Friedrichs CT. 2020. Secchi Disk Measurements in Turbid Water. *J. Geophys. Res. Oceans*, vol. 125, no. 5. doi: 10.1029/2020JC016172.
- Umwali ED, Kurban A, Isabwe A, Mind’je R, Azadi H, Guo Z, Udahogora M, Nyirarwasa J, Nzabarinda V, Gasirabo A, Sabirhazi G. 2021. Spatio-seasonal variation of water quality influenced by land use and land cover in Lake Muhazi, *Sci. Rep.*, vol. 11, no. 1, pp. 1-16. doi: 10.1038/s41598-021-96633-9.
- Wymore AS, Leon MC, Shanley JB, McDowell WH. 2019. Hysteretic response of solutes and turbidity at the event scale across forested tropical montane watersheds, *Front. Earth Sci.*, vol. 7, 452-302. doi: 10.3389/feart.2019.00126.
- Ahonen SA, Vuorio KM, Jones RI, Hämäläinen H, Rantamo K, Tirola M, Vähätalo AV. 2024. Assessing and predicting the influence of chromophoric dissolved organic matter on light absorption by phytoplankton in boreal lakes, *Limnology and Oceanography*, Vol. 69, 422-433. <https://doi.org/10.1002/lno.12495>.
- Younes H, Berggren M. 2024. Photochemical reactivity of dissolved organic carbon in subarctic lakes along a color gradient, *Inland Waters*, 14:1-2, 28-36, doi:10.1080/20442041.2024.2331957.

Response of piquín chili ecotypes (*Capsicum annuum* var. *aviculare* L.) to different shade coverage levels

Megchún-García, Juan V.²; Lucho-Constantino, Gonzalo G.^{1*}; Cruz-Ángeles R.¹; Natarén-Velázquez J.³; Moreno-Seceña, Juan C.⁴

¹ Tecnológico Nacional de México/Instituto Tecnológico Superior de Jesús Carranza, Carretera transistmica km 127+656.36, Loc. Palo dulce, 96950, Jesús Carranza, Veracruz, México.

² Tecnológico Nacional de México/ Instituto Tecnológico de Boca del Río, Carretera Veracruz-Córdoba Km. 12, 94290, Boca del Río, Veracruz, México.

³ Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Cotaxtla, Carretera Federal Veracruz-Córdoba Km 34.5, 94270, la Esmeralda, Medellín, Veracruz, México.

⁴ Colegio de Postgraduados/Campus Montecillo, Carretera Texcoco Km 36.5, Montecillo, Texcoco, 56264, Estado de México.

* Correspondence: gonzalolucho02@gmail.com

Citation: Megchún-García, J. V., Lucho-Constantino, G. G., Cruz-Ángeles R., Natarén-Velázquez, J., & Moreno-Seceña, J. C. (2026). Response of piquín chili ecotypes (*Capsicum annuum* var. *aviculare* L.) to different shade coverage levels. *Agro Productividad*. <https://doi.org/10.32854/v9t8d122>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

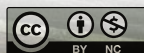
Received: October 10, 2025.

Accepted: January 19, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 243-254.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



ABSTRACT

Objective: To evaluate the effect of different levels of shade coverage using black mesh on the growth and production of two ecotypes of piquín chili cultivated with plastic mulch.

Design/methodology/approach: 16 g of fruits from wild plants of Ecotypes I and II were collected to analyze their morphological differences. Under greenhouse conditions, germination rate and germination percentage, as well as seedling height and diameter, were evaluated for both ecotypes. A completely randomized block design with eight replications was used. Subsequently, 80-day-old plants were transplanted to the field and established under four shade net treatments: T1 (0% shade), T2 (35%), T3 (50%), and T4 (90%). The variables evaluated in the field included plant height and diameter, and fruit yield.

Results: Two ecotypes of piquín chili peppers were morphologically characterized. Ecotype I showed higher emergence (70%) than Ecotype II. Under greenhouse conditions, both ecotypes exhibited similar development; however, in the field, Ecotype I showed greater vegetative development. Treatment T3 increased fruit production in both ecotypes. Shade levels did not significantly affect plant growth.

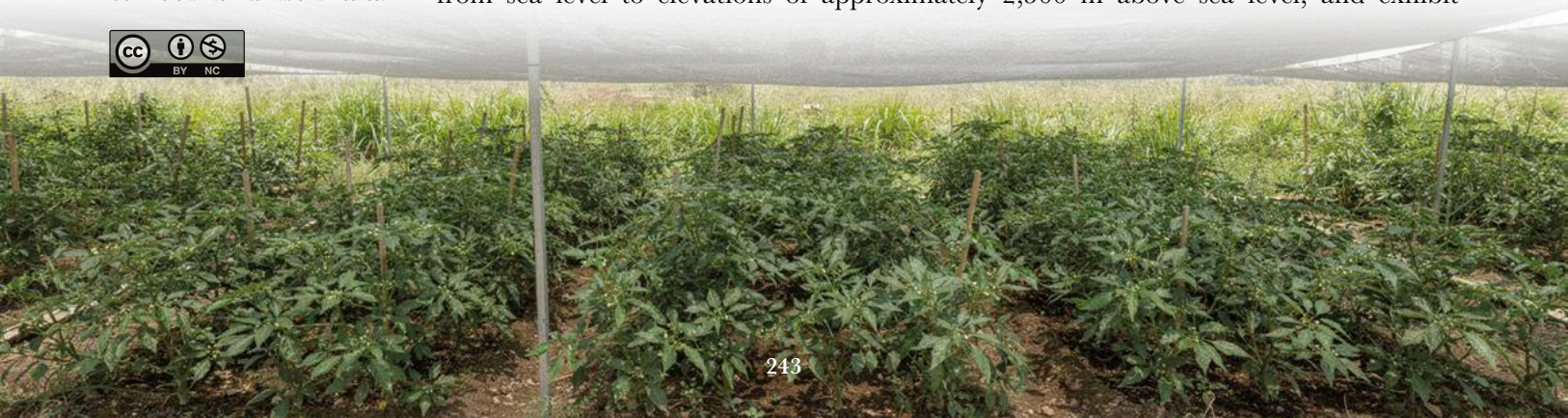
Limitations on study/implications: Piquín chili peppers are harvested in agroforestry systems. Given its high demand, shade cover promotes sustainable intensification as an agronomic alternative for its cultivation.

Findings/conclusions: Shade coverage is an intensive and sustainable strategy that helps to genetically conserve chili pepper ecotypes during production.

Keywords: Wild chili, ecotypes, shading nets, plastic padding.

INTRODUCTION

Wild chili peppers of the genus *Capsicum* L. are widely distributed in Mexico, ranging from sea level to elevations of approximately 2,500 m above sea level, and exhibit



remarkable morphological and sensory biodiversity in terms of fruit shape, size, color, flavor, and pungency. At least 30 species are recognized within the national territory (Hernandez-Verdugo *et al.*, 2019), among which five domesticated species stand out: *Capsicum annuum* L., *C. frutescens* L., *C. pubescens* Ruiz & Pav., *C. chinense* Jacq., and *C. baccatum* L. In the state of Tabasco, several groups of wild species have been collected, the most representative being *C. annuum* var. *glabriusculum* and *C. frutescens* L. (Narez-Jimenez *et al.*, 2014).

Piquin chili (*Capsicum annuum* var. *glabriusculum*) is considered the closest ancestor of cultivated varieties of *C. annuum* and is widely distributed throughout Mexican territory. Its harvest comes primarily from wild populations located in agroforestry systems, representing a significant source of income for rural communities during collection seasons (Ramírez-Novoa *et al.*, 2018). At the international level, India is emerging as Mexico's main competitor, exporting piquin chili to the United States (Balderas-Quezada *et al.*, 2023). In Mexico, most of the production destined for both domestic and international markets originates from natural wild populations (Medina *et al.*, 2010).

Regarding its morphological characteristics, piquin chili fruits are small, upright-growing, and green at the immature stage, turning bright red upon reaching physiological maturity. They may exhibit various shapes and are recognized for their high vitamin A content and antioxidant compounds. Various Indigenous communities have traditionally used these fruits in folk medicine to treat respiratory conditions such as asthma and cough, as well as to relieve sore throat and toothache, among other ailments (Balderas-Quezada *et al.*, 2023).

Piquin chili is commonly associated with thornscrub or submontane shrubland plant communities, in which the Fabaceae family predominates. These species play an important ecological role by providing shade during the early stages of development, thereby contributing to plant establishment and growth (Medina *et al.*, 2010). In the state of Sonora, piquin chili has been reported to occur in close association with *Prosopis glandulosa*, whose shade cover has been linked to the production of higher-quality fruits (Bañuelos *et al.*, 2008).

Among the main factors limiting chili production under open-field conditions are water scarcity and high temperatures. In this context, it has been reported that the combined use of plastic mulch and adequate soil moisture in huacle chili (*C. annuum* L.) grown under greenhouse conditions generated positive effects on plant phenological development, increasing the number of flower buds by 57%, flowers by 83%, fruits by 45%, leaf dry weight by 41.9%, fruit weight by 50.6%, and leaf area and leaf area index by 47% (Sanjuan *et al.*, 2022).

Recent studies have explored alternative production strategies under controlled conditions. In the state of Veracruz, Mexico, for example, the performance of *C. annuum* var. *aviculare* was evaluated under a high-density system (25,000 plants ha⁻¹) with the use of plastic mulch, obtaining yields exceeding 7 t ha⁻¹ (Megchún-García *et al.*, 2024).

Currently, there is a notable lack of specialized technologies for the agronomic management of piquin chili (*Capsicum annuum* var. *glabriusculum*) under intensive production systems (Ramírez-Novoa *et al.*, 2018). Despite this, in Saltillo, Coahuila, the effect of

Raschel-type shade nets with 30% shading and different colors (black, red, blue, and white), with 6×8 mm openings, was evaluated in the cultivation of *C. annuum* var. *glabriusculum*. The results indicated that white and blue nets significantly increased yield, as well as fruit number and size (Paredes-Jácome *et al.*, 2020).

In bell pepper (*C. annuum* L.) crops, the use of black shade netting promoted increases in relative humidity, plant height, and leaf area (Ayala-Tafoya *et al.*, 2015). This same netting has proven effective in reducing direct solar radiation, thereby helping to mitigate sunscald damage in fruits and to lower ambient temperature. Furthermore, its use recreates conditions similar to the natural habitat of piquin chili, favoring plant physiological development and improving fruit quality compared to open-field cultivation systems (Ayala-Tafoya *et al.*, 2011). Based on the above, the effect of different levels of shade coverage using black netting on the growth and production of two ecotypes of piquin chili cultivated with plastic mulch was evaluated. It was hypothesized that the application of different shading levels positively influences vegetative development and yield performance in at least one of the evaluated ecotypes.

MATERIALS AND METHODS

The study was conducted at the facilities of the Tecnológico Nacional de México/ Instituto Tecnológico Superior de Jesús Carranza, located in the municipality of Jesús Carranza, Veracruz, Mexico.

Fruit collection

Fruits were collected from wild plants exhibiting a healthy appearance and intense green color in the Ejido La Revolución community, San Juan Guichicovi, Oaxaca. Fruits from two piquin chili ecotypes, designated Ecotype I and Ecotype II, were selected at the mature stage. Subsequently, the fruits were exposed to sunlight for 24 h for drying.

Seed germination and seedling production

Seeds from Ecotypes I and II were treated with a growth promoter (HIGH PLANT[®]) at a concentration of 0.8 mL L⁻¹ of water for 24 h. The formulation of the promoter contained the following components: nitrogen (N) 0.01%, phosphorus (P) 0.02%, potassium (K) 0.02%, and gibberellic acid (GA₃) 3.30%. After completion of the treatment, seeds that settled at the bottom of the container were selected for use in the experiment.

A total of n=100 seeds from each ecotype were sown in 200-cell polystyrene trays using a substrate composed of a mixture of sand, sawdust, and vermicompost in a 1:2:2 (v/v) ratio. Seedlings emerged 11 days after sowing (DAS), and when they reached 15 cm in height, they were transplanted into 23×30 cm polyethylene bags.

During the growth period, seedlings were irrigated with water every three days and fertilized every eight days with Multiagro[®] at a dose of 10 mL L⁻¹ of water. For preventive pest management, an organic neem extract (Biocontrol[®]) was applied at a rate of 10 mL L⁻¹ of water. Additionally, during the seedling and transplant stages, Raizal[®] was applied at a dose of 10 g L⁻¹ of water using the drenching method.

Treatments

At 80 days of growth, the plants (32 per ecotype) were transferred to a shade-house system, where raised beds measuring 30×50 cm were established, with a length of 4 m. To conserve substrate moisture, gray plastic mulch (Tacsá[®]) was used and secured with industrial tape (Offiland[®]). Each plant received 500 g of vermicompost. The shade-house system was installed in an open-field area, orienting the shade net from east to west. Each shading level covered an area of 16 m², and the distance between treatments was 4 m.

During transplanting into the shade-house system, a hormonal biostimulant with immunopotentiating properties (X-pledor[®]) and a rooting agent (Raizal[®]) were applied twice, with an eight-day interval between applications. The experimental design was a completely randomized block design with eight replications and four treatments, consisting of different shading percentages: T1 (control, 0% shade net), T2 (35% shade net), T3 (50% shade net), and T4 (90% shade net).

For the morphological characterization of fruits from the mother plants, 16 g of fruits from each ecotype were collected. Fruit length, fruit width, the fruit length-to-width ratio (FL/FW), number of fruits per plant, number of seeds per fruit, and fruit color were measured.

Germination percentage was also evaluated by recording daily the number of seeds showing radicle emergence (2 mm) up to 25 DAS. The Mean Germination Rate (MGR) was calculated using the following formula:

$$MGR = n / t$$

where: *MGR* is the mean germination rate; *n* is the total number of germinated seeds, and *t* is the time from sowing until the last seed germinated.

Emergence percentage was calculated as the number of emerged seedlings divided by the number of seeds sown × 100.

Seedling growth evaluation was initially conducted during the greenhouse stage up to 72 DAS. Subsequently, after transplanting into the shade-house system, monitoring continued until 152 DAS. In both phases, plant height and stem diameter were recorded. Measurements were taken at eight-day intervals, beginning at 16 DAS for seedlings in the greenhouse stage. For plants transplanted into the shade-house system, data recording began at 80 DAS. Measurements were performed using a 3 m measuring tape (Truper[®]) and a caliper (Pretul[®]). Data were recorded in spreadsheets using Microsoft Excel[®] software.

Statistical analysis

Data were analyzed using analysis of variance (ANOVA) followed by Tukey's *post hoc* test ($P \leq 0.05$) to determine differences between ecotypes. The statistical software MINITAB, version 17, was used.

RESULTS AND DISCUSSION

Table 1 presents the morphological results of the fruits from the studied ecotypes. Fruits of Ecotype I had an average length of 1.61 ± 0.02 cm, whereas fruits of Ecotype II were longer, reaching an average of 2.51 ± 0.04 cm. The FL/FW ratio showed that fruits of Ecotype II were more elongated or narrower compared to those of Ecotype I.

Regarding width, fruits of Ecotype I were slightly wider and, in addition, this ecotype produced a greater number of fruits per plant compared to Ecotype II. Significant differences ($P \leq 0.05$) were recorded between the two ecotypes in terms of the number of seeds. At maturity, both ecotypes exhibited red-orange coloration. However, the most distinctive characteristic was the shape of the fruit apex: Ecotype I was characterized by an oval-shaped tip, whereas Ecotype II exhibited a pointed tip.

These morphological differences may be associated with structural factors derived from the adaptation of the ecotypes to different local microclimates. Hernández-Verdugo *et al.* (2012) indicate that climatic factors such as temperature, water availability, and human intervention directly influence the phenotype of wild chili populations. Likewise, Zhiglia *et al.* (2014) report that the genus *Capsicum* is characterized by wide variability in fruit type, color, shape, flavor, and phytochemical content. In the case of wild chili (*Capsicum annuum* var. *glabriusculum*), traits such as the FL/FW ratio, fruit shape, and apex shape have been identified as key characters for distinguishing among populations (Alcalá-Rico *et al.*, 2022).

Emergence percentage

ANOVA showed significant differences ($P \leq 0.05$) in emergence percentage between Ecotype I and Ecotype II. In both cases, emergence began at 10 DAS, with the appearance of two seedlings in Ecotype I and three in Ecotype II. By 14 DAS, Ecotype I reached 70% emergence, whereas Ecotype II reached 55%. These percentages remained constant until 20 DAS (Figure 1).

Mean germination rate was higher in Ecotype I, with a value of 3.5, compared to Ecotype II, which recorded a rate of 2.75. These results suggest that Ecotype I has greater germinative capacity under the evaluated experimental conditions.

Similar findings have been reported in previous studies. Research on seeds of *Capsicum annuum* L. var. *glabriusculum* (chiltepín) treated with gibberellic acid showed 97% germination at eight days and an average seedling height of 6.5 cm at 30 days under greenhouse

Table 1. Morphological characteristics of fruits from Ecotype I and Ecotype II of *Capsicum annuum* var. *aviculare* collected from mother plants in the Ejido La Revolución, San Juan Guichicovi.

Characteristics of the fruit	Ecotype I	Ecotype II
Fruit length (cm)	1.61 ± 0.02	2.51 ± 0.04
Fruit width (cm)	0.76 ± 0.02	0.69 ± 0.01
FL/FW	2.14 ± 0.07	3.65 ± 0.07
Number of fruits per plant	204	138
Number of seeds per fruit	20.6 ± 1.19	22.7 ± 2.49
Fruit color at maturity	Red-orange	Red-orange

FL/FW: ratio of the length and width of the fruit.

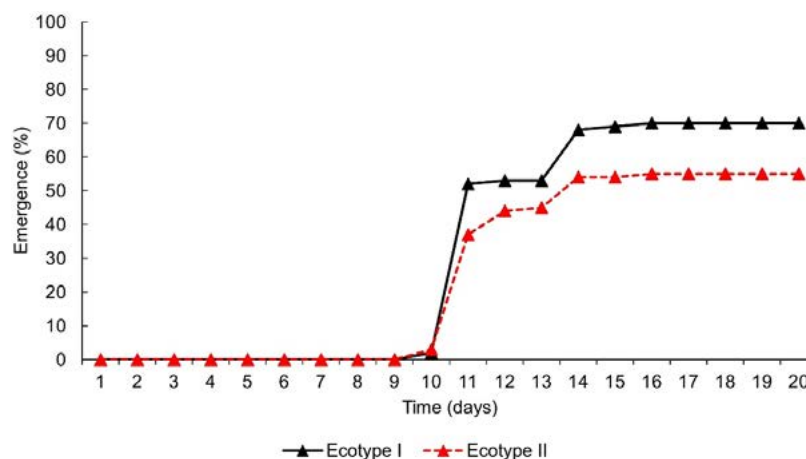


Figure 1. Emergence percentage of Ecotype I and Ecotype II of *Capsicum annuum* var. *aviculare*.

conditions (Araiza *et al.*, 2011). On the other hand, González *et al.* (2015) evaluated the effect of the biostimulant Biozyme TF (gibberellic acid 31 ppm + indoleacetic acid 31 ppm + zeatin 83 ppm) at 1.6%, applied by seed immersion for 24 h. In their study with *Capsicum annuum* L. var. *glabriusculum*, they achieved 86% germination at 12 days after sowing, indicating a positive effect of the hormonal treatment.

Seedling height and stem diameter under greenhouse conditions

No significant differences were observed in seedling height between Ecotypes I and II (Figure 2a). Ecotype I showed a height range from 3.4 ± 0.03 cm to 22.5 ± 0.16 cm, whereas Ecotype II ranged from 3.4 ± 0.00 cm to 21.0 ± 0.00 cm. From 48 DAS onward, seedlings of Ecotype I were slightly taller than those of Ecotype II. Regarding stem diameter, a trend similar to that observed for seedling height was recorded. Values for Ecotype I ranged from 0.10 ± 0.00 cm to 0.31 ± 0.00 cm, while Ecotype II ranged from 0.10 ± 0.00 cm to 0.30 ± 0.00 cm. A slight increase in stem thickness was observed in both ecotypes from 56 DAS to 72 DAS. The absence of differences in height and stem diameter between Ecotypes I and II indicates that, despite possible genetic variation, both exhibited similar vegetative development under controlled growing conditions. The slight variations observed during the seedling stage may be attributed to differences in cell elongation rate and differential assimilation of nutrients contained in the growth promoter used. Previous studies support these findings. Cano *et al.* (2015) evaluated 16 accessions of *Capsicum annuum* var. *glabriusculum* treated with gibberellic acid, potassium nitrate, and hydrogen peroxide. In that study, gibberellic acid was the treatment that most strongly promoted germination and growth rate, particularly in accessions from Acajoneta and Tuxpan, which reached germination rates of up to 70%. Furthermore, low germination in these accessions was mainly attributed to physiological dormancy.

Plant height under black shade net conditions

In the evaluation of the different shading levels applied in the shade-net system, no statistically significant differences ($p \leq 0.05$) were found among treatments for Ecotypes I

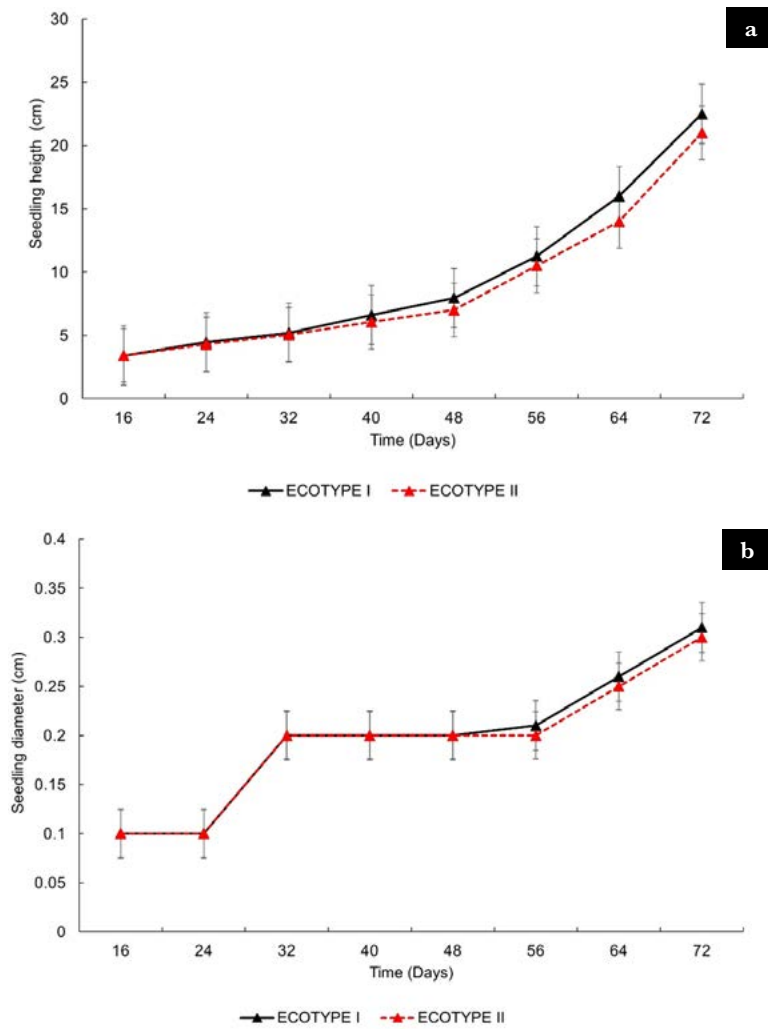


Figure 2. Height (a) and stem diameter (b) of seedlings of Ecotypes I and II of *Capsicum annuum* var. *aviculare* grown under greenhouse conditions.

and II (Figure 3a and 3b). It is important to note that, during the productive stage, plants of Ecotype I were generally taller than those of Ecotype II. Plants of Ecotype I exposed to 90% shading (T4) were the tallest among treatments, reaching an average height of 77 ± 0.32 cm at 152 DAS, compared with plants grown without shading (T1), which averaged 62.5 ± 3.0 cm (Figure 3a).

In contrast, Ecotype II exhibited a different growth pattern compared to Ecotype I. Plants grown under the different treatments showed similar height, except for those under T2, which were slightly shorter during the productive stage (Figure 3b). Slower growth was observed in plants under T2 and T3 between 96 and 112 DAS; however, during the productive stage, no significant differences were recorded compared to the other treatments. Plants of chile piquín (*Capsicum annuum* var. *aviculare*) under T4 (90% shade) reached similar sizes by 104 days of age, exceeding 65 cm in height. Plants of chile piquín (*C. annuum* var. *aviculare*) grown under plastic cover have shown positive effects on growth under open-field conditions, reaching 68 cm at 97 days (Megchun *et al.*, 2024). Our results indicate that the

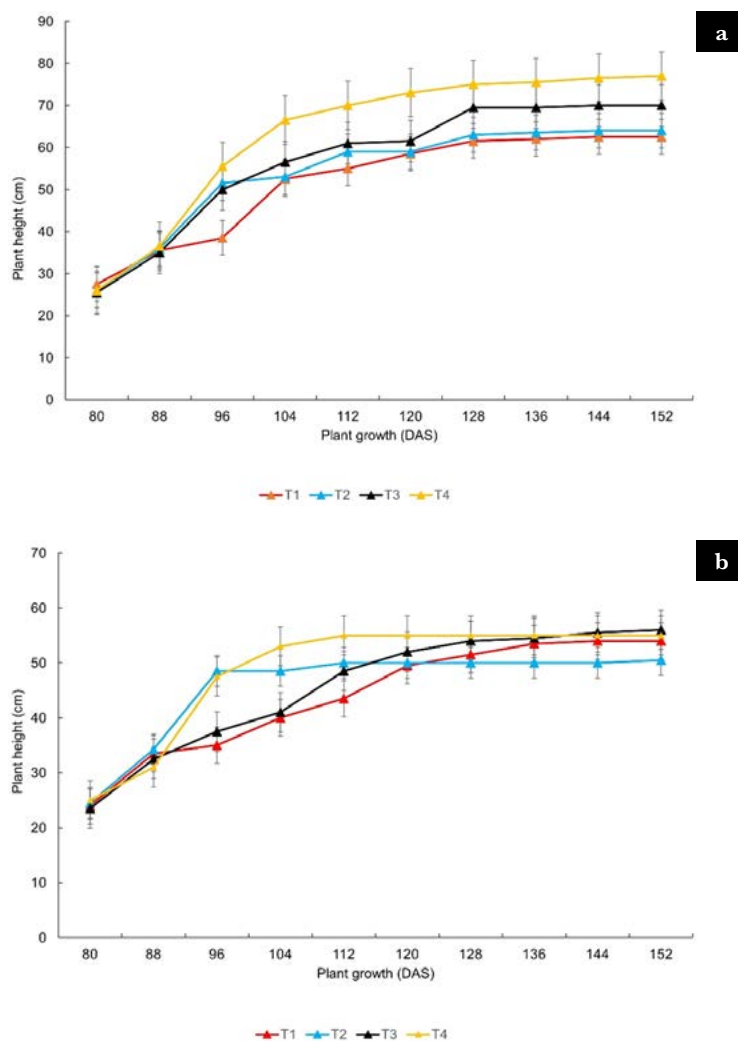


Figure 3. Plant height at 80 DAS of Ecotype I (a) and Ecotype II (b) grown under a shade-net system with different shading levels. T1: no shade net; T2: 35% shade net; T3: 50% shade net; and T4: 90% shade net. Means \pm standard error for each treatment. DAS: days after sowing.

combined use of plastic mulch and 90% shade net under open-field conditions enhances the development of chile piquín plants, as plant height increases in response to reduced light availability.

Stem diameter of plants grown under black shade net conditions

Under the shade-net system, plants of Ecotype I evaluated at 80 DAS under treatment T3 exhibited a significantly greater stem diameter during the first two weeks compared to the other treatments (Figure 4a). However, between 104 and 152 DAS, no significant differences in stem diameter were observed among the shading treatments and the control plants (T1).

For Ecotype II, plants under T4 showed a slight increase in stem diameter at 88 DAS. In contrast, plants under T1 were thinner between 96 and 120 DAS, which was

associated with increased plant height (Figure 3). At 152 DAS, no significant differences in stem diameter were recorded between shaded plants and the control group (Figure 4b). Overall, no significant differences in stem thickness were observed between Ecotypes I and II under the shade-house system (Figure 4). These results indicate that both ecotypes follow a similar growth pattern with respect to stem diameter. Additionally, a possible relationship between increased stem thickness and greater plant height was observed, suggesting that both traits may be developmentally coordinated and potentially regulated by genetic mechanisms. It is worth noting that these results differ from those reported by Paredes-Jacóme *et al.* (2019), who observed that chile piquín grown in macrotunnels with 30% white Raschel shade net exhibited an average basal stem diameter of 6.29 mm, whereas plants grown under black net reached 4.15 mm.

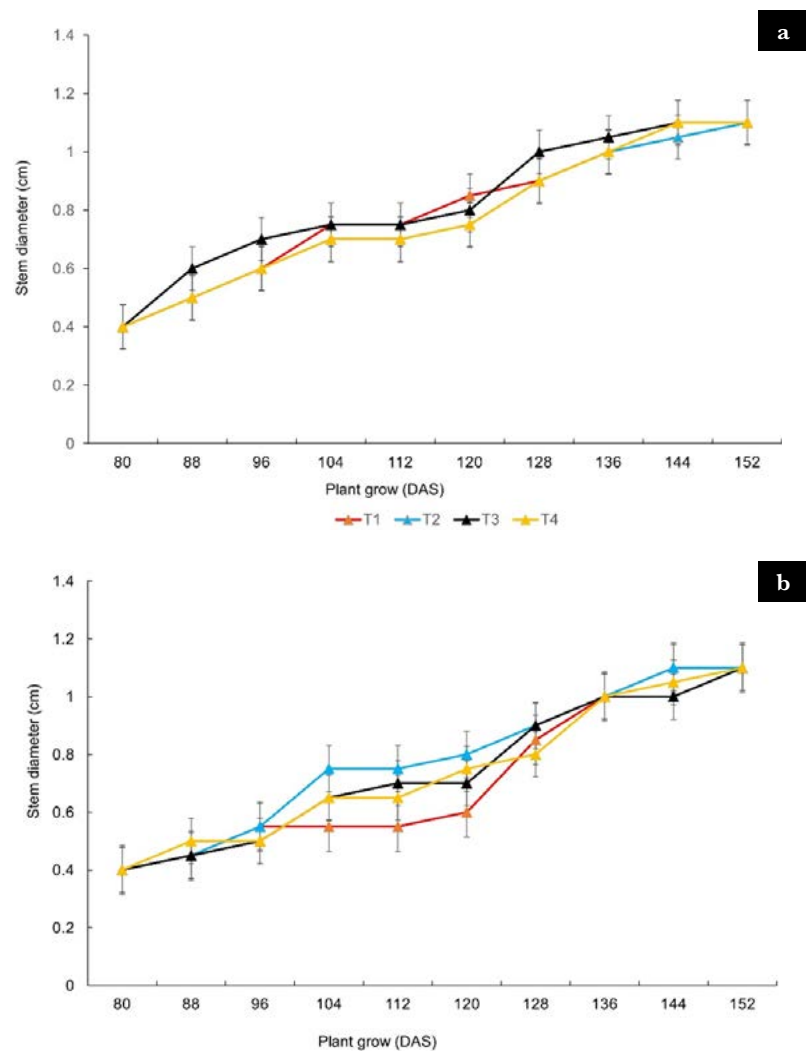


Figure 4. Stem diameter of plants at 80 DAS of Ecotype I (a) and Ecotype II (b) grown under a shade-net system with different shading levels. T1: no shade net; T2: 35% shade net; T3: 50% shade net; and T4: 90% shade net. Means \pm standard error for each treatment. DAS: days after sowing.

Fruit production under black shade net conditions

Significant differences in fruit production were found between the evaluated ecotypes ($p \leq 0.05$), with Ecotype I exhibiting higher productivity than Ecotype II across the different shading levels (Table 2). Within Ecotype I, treatment T3 had the greatest positive effect on fruit production, with an average of 310 ± 4.48 fruits per plant. For Ecotype II, treatments T3, T4, and T2 produced a higher number of fruits compared to the non-shaded treatment (T1), with T3 being the most productive, averaging 185 ± 1.41 fruits per plant.

Table 2. Number of fruits obtained under the shade-net system with different shading levels.

Treatment	Ecotype I	Ecotype II
T1	235 ± 8.07 b	153 ± 4.48 b
T2	249 ± 8.37 b	168 ± 5.13 a
T3	310 ± 4.48 a	185 ± 1.41 a
T4	256 ± 1.45 b	174 ± 1.69 a

T1: no shade net; T2: 35% shade net; T3: 50% shade net; and T4: 90% shade net. Means followed by different letters are significantly different (Tukey, $p \leq 0.05$) within each ecotype.

Studies conducted in Sonora, Mexico reported that the dry fruit yield of chiltepín (*Capsicum annuum* var. *glabriusculum*), harvested every three days, was 1.45 times higher under greenhouse conditions compared to plants grown under mesquite (*Prosopis* sp.) stands. Furthermore, recent research has indicated that chiltepín production can be significantly improved when cultivated under colored shade nets or structures with anti-aphid mesh walls (Caughey *et al.*, 2020). The use of white and blue shade nets increases yield, fruit number, and fruit size (Paredes-Jacóme *et al.*, 2019). Chiltepín is considered a fruit of high nutritional relevance. In this context, Reyes *et al.* (2018) demonstrated that the use of a blue shade net with 30% shading had a positive effect on vitamin C content and antioxidant properties of the fruits compared to plants grown under open-field conditions with a 30% black shade net. On the other hand, the use of plastic mulch has shown additional benefits in the production of *Capsicum annuum*, such as huacle chili. According to Sanjuan *et al.* (2022), this strategy improved soil moisture content and resulted in an 85% increase in flower bud formation, an 89% increase in open flowers, and a 65% increase in fruit production under greenhouse conditions. Black shade nets help reduce temperature and protect fruits from sun damage; therefore, their effect may vary depending on shade density (Ayala-Tafoya *et al.*, 2015).

CONCLUSIONS

Seedlings of Ecotypes I and II grown under greenhouse conditions at 72 DAS showed no differences in height or stem diameter. However, after transplanting to the field, plants of Ecotype I were taller than those of Ecotype II during the productive stage at 152 DAS. The different shading levels did not have a significant impact on plant growth. Nevertheless, the 50% shading treatment (T3) enhanced fruit production in both ecotypes, with Ecotype

I producing 1.68 times more fruits during the productive stage compared to Ecotype II. Therefore, Ecotype I of *Capsicum annuum* var. *aviculare* represents a viable alternative for establishment and production under 50% shade-net conditions (T3).

ACKNOWLEDGMENTS

The authors express their gratitude to Felipe de Jesús Leandro Martínez, a student in the Agronomy Engineering program at the Instituto Tecnológico Superior de Jesús Carranza, for his valuable collaboration in providing the plant material and for his contribution to the agronomic management of the plants, which supported the development of this research.

REFERENCES

- Alcalá-Rico, J. S. G. J., Ramírez-Meraz, M., Maldonado-Moreno N., Borja-Bravo M., Camposeco-Montejo N., López-Benítez A. (2023) Variación morfológica en frutos de genotipos de chile piquín (*Capsicum annuum* var. *glabriusculum*) del Noroeste y Centro de México. *Ecosistemas y Recursos Agropecuarios* 10(2): e3482. <https://doi.org/10.19136/era.a10n2.3482>
- Araiza L. N., Araiza L., E., Martínez M., J., G., (2011). Evaluación de la germinación y crecimiento de plántula de chiltepín (*Capsicum annuum* L.) variedad *glabriusculum*) en invernadero. *Rev. Colomb. Biotecnol.* 8(2): 170-175.
- Ayala-Tafoya F., Zatarain-López, D., Valenzuela-López, M., Partida-Ruvalcaba, L., Velázquez-Alcaraz, T., Díaz-Valdés, T., Osuna-Sánchez, J., (2011). Crecimiento y rendimiento de tomate en respuesta a radiación solar transmitida por mallas sombra. *Terra Latinoamericana*, 29(4), 403-410.
- Ayala-Tafoya F., Sánchez-Madrid R., Partida-Ruvalcaba L., Yáñez-Juárez G., Ruiz-Espinosa H., Velázquez-Alcaraz T. de J., Valenzuela-López M., Parra-Delgado Martín. (2015). Producción de pimiento morrón con mallas sombra de colores. *Revista fitotecnia mexicana vol.* 38(1): 93-99.
- Balderas Quezada, K. I., Piña Ramírez, F. J., García Muñoz, S. A., Soto Parra, J. M., & Yáñez Muñoz, R. M. (2023). Chile Piquín (*Capsicum annuum* var. *Glabriusculum*). Tesoro Picante de la Naturaleza. *Revista Biológico Agropecuaria Tuxpan*, 11(2): 18-23. <https://doi.org/10.47808/revistabioagro.v11i2.485>
- Bañuelos N., Salido P. L., Gardea A., (2008) Etnobotánica del chiltepín. Pequeño gran señor en la cultura de los sonorenses. *Estudios Sociales* 16(32): 7-29.
- Cano V. A., López P. C., Zavaleta M. H. A., Cruz H. N., Ramírez R. I., Gardea B. A., González H. V. A. (2015). Variación en grados de latencia en semillas entre colectas de chile piquín (*Capsicum annuum* var. *glabriusculum*). *Botanical Sciences* 93(1): 175-184. <https://doi.org/10.17129/botsci.138>
- Caughey E. D. M., Buitimea C. G. V., Buitimea C. N. E., Ayala A. G. I., Ochoa M. A. O. (2020). Propiedades fisicoquímicas y rendimiento de frutos de chile chiltepín (*Capsicum annuum* var. *glabriusculum* Dunal) cultivados bajo diferentes condiciones de crecimiento. *IDESIA*. 38(3): 77-86.
- González C. N., Jiménez V. R., Guerra B. E. C., Silos E. H., Payro de la C. E. (2015). Germinación del chile amashito (*Capsicum annuum* L. var. *glabriusculum*) en el sureste mexicano. *Revista mexicana de ciencias agrícolas* 11: 2211-2218.
- Hernández-Verdugo, S., Dávila P., Oyama K. (1999). "Síntesis del conocimiento taxonómico, origen y domesticación del género *Capsicum*". *Bol. Soc. Bot. Méx.*, 64: 65- 84. DOI:10.17129/botsci.1583.
- Hernández-Verdugo, S., Flor, P. F., Pacheco, O. A., López, E. R. G., Villareal, R. M., Parra, T. S. y Osuna, T. (2012). Caracterización y variación ecogeográfica de poblaciones de chile (*Capsicum annuum* var. *glabriusculum*) silvestre del noroeste de México. *Polibotanica*. 33:175-191.
- Medina M. T., Villalón M. H., Pérez H. J. M., Sánchez R. G., Salinas H. S. (2010). Avances y perspectivas de investigación del chile piquín en Tamaulipas, México. *CienciaUAT*. 4(4): 16-21.
- Megchún-García JV, Rebollo-Martínez A, Del Angel-Pérez AL, Nataren-Velázquez J, Capetillo-Burela A. (2024) Chile piquín (*Capsicum annuum* var. *aviculare*) establecido en un revestimiento de plástico y arreglos espaciales. *Ecosistemas y Recursos Agropecuarios* 11(3): e3984. <https://doi.org/10.19136/era.a11n3.3984>
- Narez-Jiménez, Carlos A., de-la-Cruz-Lázaro, Efraín, Gómez-Vázquez, Armando, Castañón-Nájera, Guillermo, Cruz-Hernández, Aldenamar, & Márquez-Quiroz, César. (2014). La diversidad morfológica in situ de chiles silvestres (*Capsicum* spp.) de Tabasco, México. *Revista fitotecnia mexicana*, 37(3): 209-215. Recuperado en 08 de junio de 2025, de http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0187-73802014000300005&lng=es&tlng=es.

- Paredes-Jácome, J. R., Mendoza V. R., Pérez R. M. A., Robledo T. V., Moreno L. S. (2019). Comportamiento agronómico de ecotipos de chile piquín bajo cubiertas fotoselectivas. *Ingeniería agrícola y biosistemas*, 11(1): 53-67. <https://doi.org/10.5154/r.inagbi.2018.05.011>
- Ramírez-Novoa, U. I., Cervantes-Ortiz, F., Montes-Hernández, S., Raya-Pérez, J. C., Cibrián-Jaramillo, A., Andrio-Enriquez, E. (2018). Diversidad morfológica del chile piquín (*Capsicum annuum* L. var. *glabriusculum*) de Querétaro y Guanajuato, México. *Revista mexicana de ciencias agrícolas*, 9(6): 1159-1170. <https://doi.org/10.29312/remexca.v9i6.1581>
- Reyes A. D. J., Pinedo E. J. M., Robledo T. V., Mendoza V. R., López P. C. U., Hernández F. A. D. (2018). Propiedades fisicoquímicas y actividades antioxidante de chiltepín cultivado bajo mallas sombra de colores. *Investigación y desarrollo en ciencia y tecnología de alimentos*. 3:535-540.
- Sanjuan M. J., Ortiz H. Y. D., Aquino B. T., Cruz I. S., Pérez P. R. (2022). Respuesta del chile Huacle (*Capsicum annuum* L.) al estrés hídrico bajo invernadero. *Agricultura, Sociedad y Desarrollo*. 19(4): 421-435. <https://doi.org/10.22231/asyd.v19i4.1382>
- Zhigila, D.A., AbdoulRahaman, A. A., Kolawole, O.S., Oladele, F.A. (2014). Fruit Morphology as Taxonomic Features in Five Varieties of *Capsicum annuum* L. Solanaceae. *Journal of Botany*: 1-6- <https://doi.org/10.1155/2014/540868>



Scientific production trends on *Macrobrachium acanthurus*: A Bibliometric and network analysis based on Scopus

Pérez-De Jesús, Diana¹; Reta-Mendiola, Juan L.^{1*}; Asiain-Hoyos, Alberto¹; Díaz-Rivera, Pablo¹; Oscaranza-Joya, Valeria S.²; Chong-Carrillo, Olimpia^{2,3}; Vega-Villasante, Fernando²

¹ Colegio de Postgraduados Campus Veracruz, Programa de Posgrado en Agroecosistemas Tropicales. Mpio. Manlio F. Altamirano, Veracruz, México, C.P. 91690.

² Universidad de Guadalajara, Centro Universitario de la Costa, Laboratorio de Calidad de Agua y Acuicultura Experimental, Departamento de Ciencias Biológicas, Puerto Vallarta, Jalisco, México, C.P. 48280.

³ Investigadoras e Investigadores por México, Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECIHTI), Ciudad de México, México, C. P. 03940.

* Correspondence: jretam@colpos.mx

ABSTRACT

Objective: This study presents a bibliometric analysis of scientific publications on *Macrobrachium acanthurus*, aiming to identify strengths and weaknesses in the development of research on this species.

Design/methodology/approach: One hundred scientific articles were retrieved from the Scopus database to identify the most relevant authors, institutions, countries, journals, and subject areas. The records were refined and standardized to avoid duplication, and a descriptive analysis was conducted using frequency and percentage distribution. Additionally, VOSviewer software was used to construct co-authorship, keyword co-occurrence, and international collaboration network maps.

Results: In terms of individual productivity, the authors Bertini, Hernández-Hernández, and Freire lead in number of publications. The journals with the highest number of articles were the Latin American Journal of Aquatic Research and Crustaceana. The thematic analysis identified five main areas: reproduction and development, conservation and sustainable aquaculture, genetics and molecular biology, nutrition and feed; and biotechnology and applications. VOSviewer maps confirmed the existence of consolidated collaboration clusters, although with some groups remained isolated, and highlighted the centrality of Brazil and Mexico in international networks.

Limitations on study/implications: The analysis was limited to the Scopus database; therefore, variations may arise if other databases are included.

Findings/conclusions: The results indicate that research is primarily concentrated in Brazil and Mexico. The University of São Paulo, São Paulo State University, the Federal University of Paraná, the National Autonomous University of Mexico, and the University of Guadalajara emerge as the leading academic institutions. This study provides an integrated overview of the dynamics, gaps and research opportunities related to *Macrobrachium acanthurus*, offering valuable insights to guide scientific agendas, foster collaboration strategies, and support the aquaculture development of native species.

Keywords: *Macrobrachium* sp., Bibliometrics, Scientific collaboration, VOSviewer, Sustainable aquaculture.

Citation: Pérez-De Jesús, D., Reta-Mendiola, J. L., Asiain-Hoyos, A., Díaz-Rivera, P., Oscaranza-Joya, V. S., Chong-Carrillo, O., & Vega-Villasante, F. (2026). Scientific production trends on *Macrobrachium acanthurus*: A Bibliometric and network analysis based on Scopus. *Agro Productividad*. <https://doi.org/10.32854/y47wr437>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: October 13, 2025.

Accepted: January 22, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 255-266.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

The genus *Macrobrachium* (Bate, 1868) comprises more than 238 species distributed in rivers and freshwater bodies across tropical and subtropical regions worldwide and represents the most diverse group within the family Palaemonidae. Many of these species support artisanal fisheries and hold economic, social, and cultural importance, in addition to their potential for aquaculture development.

Scientific research on the genus has shown a marked bias toward a few species of global commercial interest, particularly *M. rosenbergii*, which accounts for more than 60% of the published scientific output (Chong-Carrillo *et al.*, 2015).

In Latin America, previous analyses have identified Brazil and Mexico as leading research hubs in freshwater crustaceans, with significant advances in locally important species such as *M. amazonicum*, *M. tenellum*, and *M. americanum* (Chong-Carrillo *et al.*, 2018).

In Mexico, a recent analysis confirmed that although progress has been made in species of the genus *Macrobrachium*, their publication volume remains marginal compared with penaeid shrimps, particularly *Penaeus vannamei*, which accounts for approximately 75% of the national scientific output. In this context, *M. acanthurus* exhibits limited research production, reinforcing the need for specific studies to highlight its contributions and research gaps (Chong-Carrillo *et al.*, 2024).

The growing interest in *M. acanthurus* is justified by its wide distribution in American rivers, its importance in artisanal fisheries, and its potential for aquaculture.

From an aquaculture production perspective, limitations persist in the development of cultivation techniques, particularly during the larval stage, which continues to represent a technological bottleneck. There is also a need to further investigate aspects of nutrition, physiology, and immunology (Hernández-Hernández *et al.*, 2024).

Although *M. acanthurus* has approximately 100 articles indexed in Scopus, to date no analysis of the scientific production dedicated exclusively to this species has been conducted. Therefore, this study aims to fill that gap by systematizing the existing scientific output through a bibliometric analysis complemented by co-authorship, keyword co-occurrence, and international collaboration maps generated using VOSviewer.

This effort constitutes the first comprehensive approach to the publication dynamics surrounding *M. acanthurus*, including annual scientific production; production by authors, institutions, countries, journals, and subject areas; keyword connections; and co-authorship networks. Its main objective is to provide key information to guide future research and strengthen its potential aquaculture utilization.

MATERIALS AND METHODS

A total of 100 articles published on *M. acanthurus* between 1960 and 2024 were retrieved from Scopus. Duplicate documents, records without an available abstract, and documents not classified as scientific articles (*e.g.*, editorial notes or errata) were excluded. The documents were organized into CSV and Excel files. Based on the available information, authors, institutions, countries, journals, and abstracts were evaluated.

The records were cleaned and standardized to unify name variants and avoid duplication. Abstracts were examined and analyzed to identify thematic trends.

The descriptive analysis was performed using frequency counts and relative percentages, supported by spreadsheets and Python routines.

In addition to the descriptive analysis of authors, institutions, countries, journals, and abstracts, VOSviewer software (van Eck, N. J., & Waltman, L., 2010) was used to construct visualization maps of co-authorship networks, keyword co-occurrence, and international collaboration among countries. These maps enabled the identification of thematic and scientific collaboration clusters, represented in different colors according to the degree of connection.

RESULTS AND DISCUSSION

The bibliometric analysis of the 100 articles retrieved from the database made it possible to identify the main actors, institutional and geographic trends, as well as the predominant thematic areas in research on *M. acanthurus* and related species.

Scientific Production by Year (Temporal Fluctuation of Scientific Output)

The temporal analysis of publications reveals an irregular trajectory with an overall upward trend. Between the 1960s and the 1990s, scientific output remained low, ranging from 0 to 2 articles per year. A slight increase is observed after 2000, and the upward trend intensified from 2010 onward, reaching peaks of 7 to 8 articles in certain years.

These results indicate that scientific interest in *M. acanthurus* has increased markedly over the past two decades, in line with the expansion of aquaculture research and the growing recognition of the importance and conservation of native species in Latin America (Figure 1).

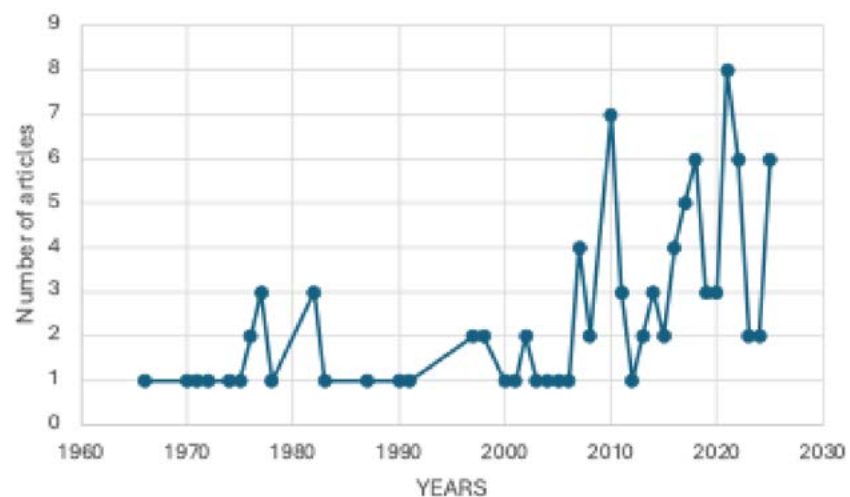


Figure 1. Chronology of publications on *Macrobrachium acanthurus* according to Scopus. Source: Authors' own elaboration.

Author productivity

A marked concentration of scientific output was observed among a small number of researchers. The most productive author was G. Bertini, with nine publications, followed by L. H. Hernández-Hernández and C. Arruda Freire, each with eight articles. Other notable contributors included L. S. López-Greco (six articles), G. Soares Moreira (five), and a group with three to four contributions, among whom S. A. Frías-Gómez, M. A. Fernández Araiza, and F. Vega-Villasante stand out. This distribution indicates the presence of consolidated research cores, supported by recurrent collaborators.

Participating institutions

Brazilian universities were predominant in the institutional distribution of publications. The Universidade de São Paulo led the ranking with 13 articles, followed by the Universidade Estadual Paulista “Júlio de Mesquita Filho” and the Facultad de Estudios Superiores Iztacala (UNAM, Mexico), each with 12 publications. Other prominent institutions included the Universidade Federal do Paraná (9 articles) and the Universidad Nacional Autónoma de México (8).

Figure 2 illustrates the strong presence of Brazilian and Mexican academic centers in research on freshwater crustaceans.

Geographic distribution

In terms of countries, Brazil accounted for the largest share of scientific output, with 59 articles (59%), followed by Mexico with 23 (23%). To a lesser extent, contributions were

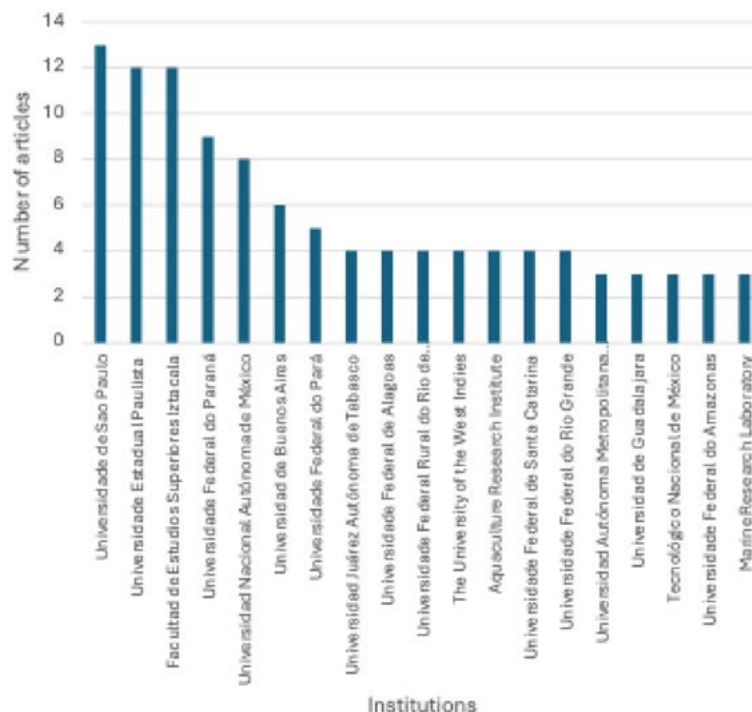


Figure 2. Most frequently cited institutions in articles on *Macrobrachium acanthurus* indexed in Scopus. Source: Authors' own elaboration.

recorded from the United States (14), Argentina (6), and Venezuela (11), as well as from European countries such as Germany and Spain, which showed sporadic contributions.

Figure 3 illustrates the predominance of Brazil and Mexico, which may be explained by the natural distribution of the genus *Macrobrachium* and the consolidation of specialized research groups focused on aquaculture and the ecology of native species.

Main publication journals

The articles were published in a diverse range of journals specializing in aquaculture, invertebrate biology, and ecology. The most representative were Latin American Journal of Aquatic Research and Crustaceana, each with seven articles, followed by Invertebrate Reproduction and Development (six articles) and Aquaculture (four).

Figure 4 suggests that publication in indexed international journals reflects a sustained effort by Latin American researchers to provide global visibility to studies conducted in the region (Figure 4).

Thematic areas

The analysis of the abstracts allowed the classification of the articles into five major knowledge areas (Figure 5):

Reproduction and development: 45 articles (24.7%), with emphasis on fecundity, morphotypes, reproductive strategies, and larval development.

Conservation and sustainable aquaculture: 34 articles (18.7%), focused on diversity, geographic distribution, population biology, and sustainable management.

Genetics and molecular biology: 33 articles (18.1%), covering gene expression, transcriptomic analyses, and molecular studies of hemocyanins.

Nutrition and feeding: 20 articles (11%), addressing diet evaluation, nutritional requirements, and micronutrient bioassays.

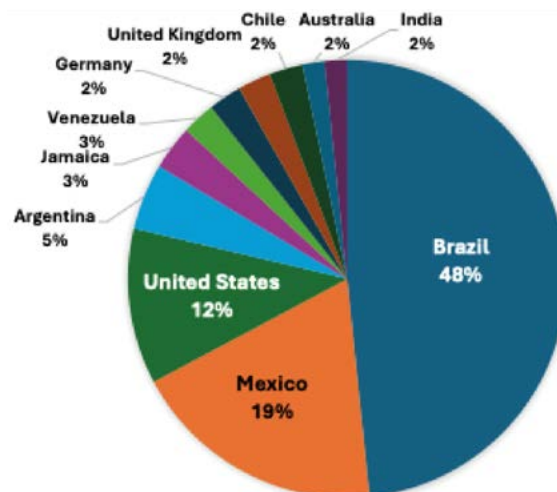


Figure 3. Publications on *Macrobrachium acanthurus* by country, with percentage of participation. Source: Authors' own elaboration.

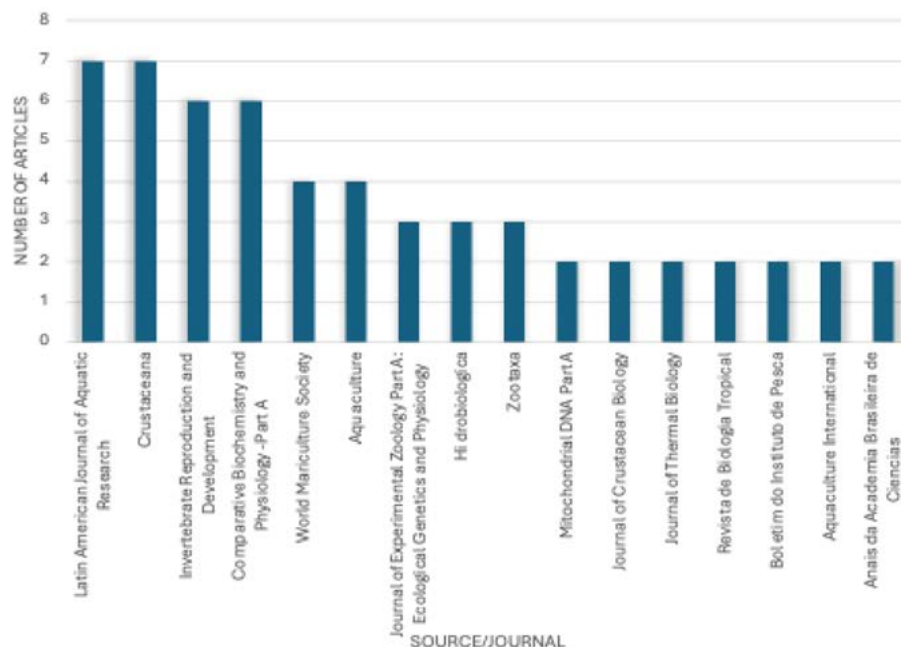


Figure 4. Most frequently cited journals in articles on *Macrobrachium acanthurus* indexed in Scopus. Source: Authors' own elaboration.

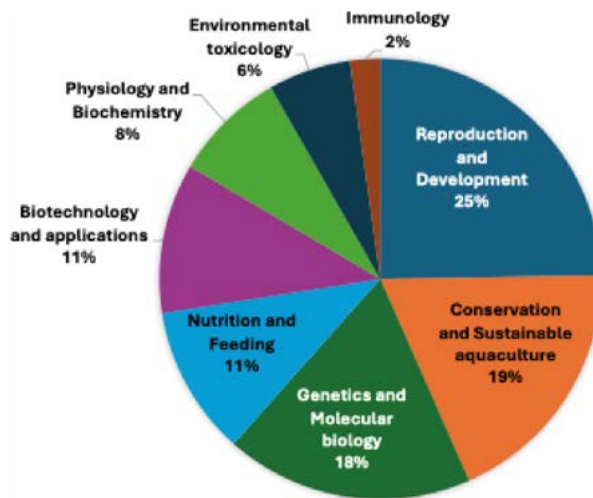


Figure 5. Thematic areas in scientific publications on *Macrobrachium acanthurus* indexed in the Scopus database, showing percentage share of participation. Source: Authors' own elaboration.

Biotechnology and applications: 20 articles (11%), related to biomedical and biotechnological uses of crustacean-derived compounds, as well as innovations in cultivation techniques.

These results reflect the thematic diversity of the research field, with a clear predominance of studies focused on reproductive biology and conservation, followed by molecular and applied approaches.

homogeneous across species: whereas *M. tenellum* and *M. americanum* have experienced specific upturns, *M. acanthurus* has maintained moderate but steady growth. Hernández-Hernández *et al.* (2024) emphasize that although the species has attracted attention due to its ecological and aquaculture relevance, the lack of progress in larviculture and cultivation techniques has constrained the consolidation of a sustained line of applied research. In this regard, the temporal curve reflects both the growing scientific recognition of the species and the structural limitations that have hindered development comparable to that of other species within the genus.

At the institutional level, the strong participation of Brazilian universities (USP, UNESP, UFPR) and Mexican institutions (UNAM and University of Guadalajara) demonstrates the consolidation of specialized research cores capable of sustaining continuous scientific production. These institutions not only lead in terms of publication volume, but also act as centers for training human resources, thereby ensuring the continuity of research lines. Interinstitutional collaboration, reflected in international co-authorships, reinforces the idea that the study of *Macrobrachium* represents a shared agenda among Latin American research groups and some international partners, mainly from the United States and Europe. This pattern is consistent with Chong-Carrillo *et al.* (2015), who emphasize that scientific production on *Macrobrachium* has historically depended on concentrated and relatively isolated research groups, with still incipient international linkages. In the case of Mexico, the situation reflects a relative lag within the genus itself. Although *M. tenellum* and *M. americanum* have shown peaks in scientific productivity, *M. acanthurus* has remained at low and constant levels, without notable upturns in recent decades (Chong-Carrillo *et al.*, 2024). This situation is related to what the same authors describe as a bias toward the cultivation of penaeids —mainly *Penaeus vannamei*— which has relegated native *Macrobrachium* species. The consequence is limited technological development for these species and a dependence on production models centered on exotic species.

The pattern observed in publication journals is consistent with the profile of the research topics addressed. The high frequency of articles in specialized journals such as *Crustaceana*, *Invertebrate Reproduction and Development*, and *Latin American Journal of Aquatic Research* reflects an orientation toward basic biology, reproduction, and ecology, whereas the presence of publications in *Aquaculture* highlights the applied relevance of these species. However, the limited publication in higher-impact international journals suggests an ongoing challenge in the internationalization and global visibility of regional research.

Regarding thematic areas, the clear predominance of studies on reproduction and development (24.7%) reflects the importance of understanding life cycles and reproductive strategies in order to overcome the main bottlenecks in the cultivation of *M. acanthurus*. In turn, the significant presence of the conservation and sustainable aquaculture category (18.7%) highlights concern for the management of natural populations and the valuation of biodiversity, responding both to artisanal fishing pressure and habitat degradation. The growing attention to genetics and molecular biology (18.1%) indicates a process of methodological modernization aimed at integrating frontier approaches to explain physiological and adaptive processes.

Finally, studies on nutrition (11%) and biotechnology (11%) provide practical solutions for cultivation systems and open up opportunities for utilization in biomedical and biotechnological sectors. This is consistent with the patterns reported by Hernández-Hernández *et al.* (2024), who emphasize that research on *M. acanthurus* has been oriented primarily toward reproductive and physiological biology, while technological application—particularly larval cultivation—continues to represent a bottleneck. Our results reinforce this critical perspective by revealing a gap between basic biological research and aquaculture application. Overall, the findings indicate that research on *Macrobrachium* is in a phase of thematic and methodological consolidation, in which classical lines of inquiry (reproduction, nutrition, physiology) coexist with emerging areas (molecular biology, biotechnology, conservation). However, several gaps persist: (i) the lack of comprehensive studies linking wild population ecology with aquaculture development; (ii) the need for stronger regional and global collaboration; and (iii) the challenge of publishing in higher-impact international journals in order to position Latin American research within a global context.

The VOSviewer maps allow the quantitative results to be contextualized. The co-authorship structure confirms the existence of consolidated research cores in Brazil and Mexico, although with limited international connections, which is consistent with the fragmentation previously reported by Chong-Carrillo *et al.* (2015, 2018). Likewise, the keyword network reinforces the centrality of topics such as reproduction, development, and aquaculture, reflecting both the continuity of traditional priorities and the absence of a strong shift toward emerging areas. Although most research is concentrated within well-defined clusters, isolated groups persist that could benefit from greater cooperation.

The keyword network supports the thematic classification derived from the abstracts, highlighting the centrality of reproduction, physiology, and conservation. This finding confirms that research priorities are aligned with the main bottlenecks in cultivation and the need to protect natural populations.

Finally, the country collaboration network underscores the regional relevance of Brazil and Mexico, while also pointing to the urgency of expanding collaboration into broader international contexts. The lack of extensive linkages may constrain the global visibility of these studies and their integration into wider scientific debates.

Overall, the evidence indicates that research on *M. acanthurus* is in a phase of thematic and methodological consolidation, but faces three main challenges: (i) overcoming the gap between basic research and technological application, particularly in larval cultivation (Hernández-Hernández *et al.*, 2024); (ii) expanding international collaboration and reducing cluster fragmentation (Chong-Carrillo *et al.*, 2015; 2018); and (iii) diversifying the research agenda in Mexico and Latin America to reduce the lag behind more extensively studied species within the genus and compared with cultivated penaeids (Chong-Carrillo *et al.*, 2024).

From a science policy perspective, these findings suggest the need to strengthen funding for native species, promote regional research networks, and link basic research with technological development in sustainable aquaculture.

CONCLUSIONS

The present bibliometric analysis of 100 articles on *M. acanthurus* reveals a scientific output concentrated in Brazil and Mexico, countries that host both the greatest natural diversity of the genus and well-established academic institutions in aquaculture and invertebrate biology. The Universidade de São Paulo (USP), Universidade Estadual Paulista “Júlio de Mesquita Filho” (UNESP), Universidade Federal do Paraná (UFPR), Universidad Nacional Autónoma de México (UNAM), and the University of Guadalajara stand out as research hubs and centers for training human resources.

The co-authorship network analysis conducted with VOSviewer confirms the presence of consolidated clusters of researchers, particularly in Brazil and Mexico, although isolated cores persist, reflecting collaboration that remains limited at the global scale. Complementarily, the country collaboration map shows the centrality of Brazil and Mexico in scientific output, with linkages primarily to the United States, Argentina, and several European countries, highlighting the need to expand international networks.

Specialized journals in invertebrate biology and aquaculture have been the main dissemination channels, ensuring thematic relevance but limiting the international visibility of the results. Integration into higher-impact forums represents both a challenge and a strategic opportunity to enhance the global projection of this research.

Regarding thematic axes, the analysis of abstracts and the keyword co-occurrence map generated in VOSviewer consistently highlighted the centrality of studies on reproduction and development, followed by conservation and sustainable aquaculture, genetics and molecular biology, and, to a lesser extent, nutrition and biotechnology. These patterns reflect a field in transition, combining classical approaches with more modern and applied approaches.

Overall, the results indicate that research on *M. acanthurus* is undergoing a phase of consolidation and diversification, although it still faces significant challenges: integrating ecological and cultivation studies, strengthening international cooperation, and achieving greater visibility in higher-impact journals.

The VOSviewer maps complement this overview by revealing the structure of collaborations and thematic interconnections, providing an integrated perspective on current dynamics and future development opportunities within the field. It is expected that the knowledge and experience generated with other species such as *M. rosenbergii* at the international level, and *M. tenellum* and *M. americanum* at the national level, will guide the direction of future R&D&I efforts related to *M. acanthurus* over the coming decades.

ACKNOWLEDGMENTS

The authors acknowledge the Ministry of Science, Humanities, Technology and Innovation of Mexico for the doctoral scholarship granted to the lead author of this study. The authors also thank the Colegio de Postgraduados and the University of Guadalajara for their support of the participating researchers.

REFERENCES

Chong-Carrillo, O., Peña-Almaraz, O. A., Aréchiga-Palomera, M. A., Nieves-Rodríguez, K. N., Palma-Cancino, D. J., Guerrero-Galván, S. R., Vargas-Ceballos, M. A., Hernández-Hernández, L. H.,

- & Vega-Villasante, F. (2024). Scientific research on crustacean farming in Mexico: A scientometric scenario. *Agro Productividad*, 17(9), 183-200. <https://doi.org/10.32854/agrop.v17i9.2946>.
- Chong-Carrillo, O., Vega-Villasante, F., Arencibia-Jorge, R., Akintola, S. L., Michán-Aguirre, L., & Cupul-Magaña, F. G. (2015). Research on the river shrimps of the genus *Macrobrachium* (Bate, 1868) (Decapoda: Caridea: Palaemonidae) with known or potential economic importance: Strengths and weaknesses shown through scientometrics. *Latin American Journal of Aquatic Research*, 43(4), 684-696. <https://doi.org/10.3856/vol43-issue4-fulltext-X>.
- Chong-Carrillo, O., Vega-Villasante, F., Maciel, C., Álvarez-González, C. A., Michán-Aguirre, L., & Arencibia-Jorge, R. (2018). Scientometrics of the genus *Macrobrachium* by using the regional PERIODICA database. *Latin American Journal of Aquatic Research*, 46(3), 581-588. <https://doi.org/10.3856/vol46-issue3-fulltext-11>.
- Hernández-Hernández, L. H., Frías-Gómez, S. A., Powell, M. S., Álvarez-González, C. A., Cortés-Jacinto, E., Cigarroa-Ruiz, L., & Arellano-Carrasco, G. (2024). Scientific knowledge of the Cinnamon River prawn *Macrobrachium acanthurus* and future perspectives for aquaculture. *Aquaculture International*, 32, 10215-10230. <https://doi.org/10.1007/s10499-024-01075-5>.
- Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 84(2), 523-538. <https://doi.org/10.1007/s11192-009-0146-3>.



Response of economic indicators of guava (*Psidium guajava* L.) production to public policies: Mexico

Ibarra-Hernández, José M.¹; De Luis-Peralta, Agustín¹; Cisneros-Núñez, Carolina^{1*}; Camarena-Rubio, Karen¹

¹ Universidad Autónoma Chapingo, Km 38.5 Carr. México-Texcoco. Chapingo, Estado de México. México. C.P. 56230.

* Correspondence: karyn.cisn@gmail.com

ABSTRACT

Objective: To estimate the profitability, competitiveness, and efficiency of guava production in Mexico in order to determine whether agricultural public policies have strengthened or undermined its economic performance. **Design/methodology/approach:** The Policy Analysis Matrix (PAM) was applied, complemented by the Relative Economic Competitiveness Index. Private prices and production costs were compiled from Mexico's guava-producing states. For each production system, data were collected on cultivated area, yield, output, production system type, input units, wages, and farm-gate and marketing prices.

Results: At private prices, 98.45% of guava production was profitable and 94.75% was competitive; under social prices, these proportions declined by 4.35 and 2.85 percentage points, respectively. Additionally, 92.88% of production exhibited comparative advantages, concentrated in 6.25% of the guava-producing states. In 93.75% of state-level production systems, agricultural policy was pivotal for sustaining guava production; conversely, in Michoacán and Aguascalientes, policy was not a determining factor. Production displayed favorable relative competitiveness for investors, but not from a social perspective.

Findings/conclusions: Guava production in Mexico showed high profitability and competitiveness under both private and social prices. Comparative advantages were identified only in the production systems of Aguascalientes and Michoacán. Overall, agricultural public policies enhanced profitability, competitiveness, and efficiency, particularly in states characterized by rainfed production systems.

Keywords: comparative advantage; competitiveness; profitability; market failure; subsidy

Citation: Ibarra-Hernández, J. M., De Luis-Peralta, A., Cisneros-Núñez, C., & Camarena rubio, K. (2026). Response of economic indicators of guava (*Psidium guajava* L.) production to public policies: Mexico. *Agro Productividad*. <https://doi.org/10.32854/bbjs5y04>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: October 24, 2025.

Accepted: January 26, 2026.

Published on-line: April 16, 2026.

Agro Productividad, 19(2). February. 2026. pp: 267-277.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

Guava (*Psidium guajava* L.) is a prominent crop in Mexico, with strong global consumer acceptance largely attributable to its contribution of health-promoting nutrients, according to the Secretaría de Agricultura y Desarrollo Rural (SADER; formerly the Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación [SAGARPA]) (SADER, 2019). From an international trade perspective, guava is one of the country's relevant fruit crops, with cultivated areas accounting for 4% of global production (Servicio de



Información Agroalimentaria y Pesquera [SIAP], 2025). Accordingly, guava production in Mexico exhibits substantial potential for profitability and competitiveness, particularly in Michoacán, Aguascalientes, and Zacatecas, which lead national output (SIAP, 2024). To consolidate this potential, public policies play a strategic role by integrating economic and productive instruments; nonetheless, their design and implementation may generate both favorable and adverse effects. On the one hand, subsidies, tax incentives, and accessible credit can reduce production costs and enhance farmers' relative profitability (SAGARPA, 2007). Conversely, SAGARPA (2007) cautions that government transfers can render the sector's profitability unsustainable. Similarly, Wenqi *et al.* (2022) contend that such instruments constrain sectoral competitiveness. González and Orrantia (2006) argue that investment should prioritize support services to increase agricultural productivity rather than focusing on expanding subsidies. In addition, SADER (2023) notes that technological modernization, improvements in irrigation systems, and training in sustainable practices raise agricultural productivity. Despite the sector's commercial dynamism and the presence of fiscal incentives in Mexico's agricultural sector, the cultivated area devoted to guava has remained stagnant; from 2000 to 2024, the planted area stayed relatively constant (SIAP, 2025). According to the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP, 2018), Mexico has the potential to expand the planted area for this crop, primarily in tropical and subtropical zones. No national-level studies have been identified that analyze guava production in Mexico using the Policy Analysis Matrix (PAM). The crop's social profitability, its comparative advantages, and the effect of public policies and market distortions on competitiveness and efficiency across producing states remain insufficiently documented. Guava was selected due to its regional importance and its sensitivity to public policy, which enables the assessment of economic effects that are less apparent in fruit crops with greater export weight. Against this backdrop, the objective of this research was to estimate the profitability, competitiveness, and efficiency of guava production in Mexico within private and social production frameworks. Specifically, the study assessed whether agricultural public policies in force as of 2024 increase these economic indicators or, alternatively, diminish them. To examine public policies, it was necessary to distinguish private profitability from social profitability in order to identify market failures and the divergences associated with State intervention.

MATERIALS AND METHODS

Information used

Statistical tests ($\alpha=0.05$) were conducted in SPSS v27 to analyze measures of central tendency for the private and social economic indicators of profitability, competitiveness, and efficiency across Mexico's guava-producing states in 2024, with the aim of drawing inferences regarding the observed differences among these indicators. The analysis did not incorporate environmental externalities. Private and social economic indicators of profitability, competitiveness, divergences, and efficiency were estimated using the Policy Analysis Matrix (PAM) proposed by Monke and Pearson (1989), based on state-level averages. This methodology is structured as a two-entry matrix in which rows correspond to revenue, tradable input costs, and domestic factor costs; the resulting balance reflects

profitability (González & Alferes, 2010). The Programa de las Naciones Unidas para el Desarrollo (PNUD, 2018) notes that social competitiveness comprises the income, health, and education dimensions. In this context, and for the purposes of the present study, the social assessment of competitiveness was grounded in the Social Competitiveness Economic Coefficient (SCEC), adopted as a technical approach to estimate the effects of public policies and market distortions on productive competitiveness evaluated at social prices. In addition, the Relative Economic Competitiveness Index (RECI) was proposed as a methodological tool to assess the private benefit-cost ratio (BCR) and social competitiveness (SCEC).

$$RECI = \frac{BCR}{SCEC}$$

The RECI makes it possible to determine the extent to which competitiveness observed under private conditions differs from that assessed from a social perspective, thereby facilitating a comparative analysis of economic efficiency.

Private profitability and competitiveness

Annual average private production prices and costs were obtained for Mexico's guava-producing states (SIAP, 2025). For each production system, information was drawn from the Comisión Nacional de los Salarios Mínimos (CONASAMI, 2023), the (INIFAP, 2025), SIAP (2025), and the Instituto Nacional de Estadística y Geografía (INEGI, 2024). The dataset included planted, harvested, and loss-affected area (ha); total output (kg) and production value (thousands of pesos); production system type (irrigated and rainfed); Guava Production Units (GPUs) (the acronym will be used consistently throughout the document to refer to guava production units); yield (kg/ha); agricultural day-labor wages; and local, national, and export marketing prices.

Private profitability (D) was estimated as the difference between total revenues (A) and the sum of tradable input costs (B) and domestic factor costs (C), incorporating subsidies into both components (Monke & Pearson, 1989). Private competitiveness was assessed using the private benefit-cost ratio (BCR), which expresses the capacity of the production system under prevailing technology, prices, and policy interventions to cover domestic factors with the value added at market prices (Monke & Pearson, 1989; SAGARPA, 2019). Values of $D > 0$ indicate profits, $D = 0$ break-even, and $D < 0$ losses. For the BCR, values < 1 indicate competitiveness, $= 1$ economic equilibrium, and > 1 a lack of competitiveness. From a policy standpoint, $D > 0$ and $BCR < 1$ indicate financial viability; values near break-even suggest vulnerability to changes in prices or costs; whereas $D < 0$ and $BCR > 1$ imply a need for interventions aimed at improving productivity, technological efficiency, or access to inputs.

Profitability and competitiveness at social prices

Social profitability (H) was estimated as the economic return obtained by valuing goods and factors of production at their opportunity cost (Monke & Pearson, 1989). It was

calculated as the difference between social revenues (E) and the sum of tradable input costs (F) and domestic factor costs (G), both evaluated at social prices. Values of $H > 0$ indicate economic efficiency and social profitability; $H = 0$ indicates recovery of the opportunity cost of resources; and $H < 0$ indicates inefficient use of factors. Social prices were estimated following SAGARPA (2019), under the assumption that they reflect values undistorted by public policy or market failures (Monke & Pearson, 1989). Their calculation used the 2024 average exchange rate (18.33 MXN/USD) (Secretaría de Hacienda y Crédito Público [SHCP], 2025), together with information on tariffs, international prices of inputs and intermediate goods, and prevailing taxes and subsidies obtained from the Servicio Nacional de Información de Comercio Exterior (SNICE, 2025) and SHCP (2023), according to the following formula:

$$P_s = \left[\left(P_m - (P_{csf} \$ (1 + VM)) + S - I(1 - C) \right) + \left(P_m - P_{csf} \$ (1 + VM) \right) + S - I \left(C \left(\frac{PC_m (1 - IVA)}{PC_m} \right) \right) \right] + \left[(P_{csf} \$ (1 + V) T \$ s) \right]$$

P_s represents the social price of inputs and intermediate products, whereas P_m is the market price of the input in the Guava Production Units (GPUs). $P_{csf} \$$ corresponds to cost, insurance, and freight (CIF) in U.S. dollars; VM and VAT refer to value-added tax rates; V denotes the import tariff; S and I correspond to subsidies and direct taxes; C is the percentage of transportation cost associated with fuel; PC_m is the market price of fuel; and $T \$ s$ is the shadow exchange rate, based on the 2024 average exchange rate. The Social Competitiveness Economic Coefficient (SCEC) was calculated as the benefit-cost ratio at social prices ($SCEC = E / (F + G)$), where E denotes revenues and $F + G$ represents factor and tradable input costs valued at opportunity cost (Monke & Pearson, 1989). Values greater than 1 indicate competitiveness, values below 1 indicate a lack of competitiveness, and a value of 1 implies that costs are only just covered.

Nominal and effective protection coefficients

Policy effects and market failures on the production system were assessed using protection coefficients. The Nominal Protection Coefficient (NPC) measures the divergence between private and social prices caused by taxes, subsidies, or other distortions (Monke & Pearson, 1989). For tradable outputs, it was estimated as $NPC_c = A/E$, where values > 1 indicate price protection (an implicit subsidy) and values < 1 indicate dis-protection or implicit taxation. For tradable inputs, it was calculated as $NPC_i = B/F$; values > 1 indicate that producers pay for inputs above their social cost, whereas values < 1 indicate subsidized inputs. Effective protection was evaluated through the Effective Protection Coefficient (EPC), which integrates the analytical framework of the Policy Analysis Matrix proposed by Monke and Pearson (1989) with methodological guidelines from the Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO, 2000), providing a robust theoretical basis for analyzing distortions in agroproductive systems. This indicator simultaneously

incorporates divergences in outputs and inputs and their effect on value added, and was estimated as $EPC = (E - F) / (A - B)$. Values of $EPC > 1$ indicate net protection for the productive activity, whereas values < 1 indicate dis-protection. Nevertheless, the NPC and EPC do not fully capture the economic incentives faced by producers (Monke & Pearson, 1989).

Divergences and efficiency

Divergences (I) between evaluations at private and social prices reflect the effects of government intervention and market failures on the profitability of production systems, allowing identification of distortions that affect the efficient allocation of resources (Monke & Pearson, 1989). This indicator was estimated as the difference between revenue at private prices (A) and revenue at social prices (E). Values of $I > 0$ indicate that the activity receives protection or benefits derived from policies or distortions that raise private profitability above social profitability; $I = 0$ suggests the absence of relevant distortions and an efficient allocation of resources; whereas $I < 0$ indicates dis-protection or implicit burdens that reduce private profitability despite economic efficiency. The magnitude and sign of I provide an objective criterion for assessing the need to adjust intervention instruments in order to improve efficiency and resource allocation in the agricultural sector. Regarding relative competitiveness, defined as the ratio between private competitiveness (BCR) and social competitiveness (SCEC), the Relative Economic Competitiveness Index (RECI) indicates that if $RECI > 1$, the project is competitive for the investor but may generate losses or negative impacts for society; if $RECI < 1$, the activity or project is socially competitive because social benefits exceed total social costs. Finally, $RECI = 0$ indicates that no external benefits or costs exist in the activity, or that they offset each other, implying the absence of market failure and an efficient allocation of resources. Economic efficiency, or comparative advantage, was assessed using the Factor Cost Coefficient (FCC) coefficient, which expresses the share of social value added allocated to covering the costs of domestic factors of production, such as labor and capital (Monke & Pearson, 1989). Both costs and revenues were valued at social prices, and the coefficient was estimated as $FCC = G / (E - F)$. Values of $FCC < 1$ indicate economic efficiency and the presence of comparative advantage, as value added is sufficient to remunerate domestic factors and generate surpluses; $FCC = 1$ reflects an economic break-even situation, generating neither residuals nor losses for the producer; whereas $FCC > 1$ indicates inefficiency, as the opportunity cost of resources is not fully covered. The sign and magnitude of the FCC enable identification of activities that use resources efficiently and those that may require improvements in productivity, technology, or factor reallocation.

RESULTS AND DISCUSSION

Private profitability and competitiveness

In Mexico, differences in domestic factors of production revealed substantial heterogeneity in guava production across states. At the national level, most guava output was profitable at private prices ($D > 0$), concentrated in a large share of the planted area and production units. This outcome exceeded that reported by González and Alferes (2010) for

maize (86.9% private profitability), reinforcing the notion that guava has strong productive potential, given that profitability is a critical driver of investment incentives (Porter, 2016). The profitability observed for guava in this study surpassed that reported for maize; however, these crops differ markedly in their productive characteristics. Whereas maize is an annual staple grain crop, guava is a perennial fruit crop, with higher initial investment requirements and a more specialized production system. The states with the highest profitability were Michoacán, Aguascalientes, and Zacatecas, which accounted for the largest share of national output and constitute the most profitable guava-producing regions. In these three states, production was also concentrated in a relatively small proportion of production units; nevertheless, they encompass an extensive cultivated area devoted to the crop. Although 91% of guava production in Yucatán was rainfed, the state exhibited high profitability; however, the area allocated to this crop is minimal (0.04%), representing a clear opportunity to expand production, particularly given its average yield of 13.5 t/ha. As proposed by INIFAP (2018), Mexico has the potential to increase the planted area for this crop, especially in tropical and subtropical zones. The lowest profitability was recorded in Guanajuato, Jalisco, the State of Mexico, Guerrero, and Nayarit, which together allocated only 7.28% of the guava-cultivated area, equivalent to 1,366 Guava Production Units (GPU) (5.34%). Low profitability may be attributable to poor yields, limited cultivated area, or high production costs. These factors may have constrained profitability and help explain why their contribution represented only 5.42% of total national output. Across states, both total revenue and total investment in guava production varied. Although the highest total costs (B+C) were observed, the states exhibiting greater competitiveness ($BCR > 1$) were those with the highest revenues (A). These differences may be influenced by the production system type, as the states showing competitiveness relied primarily on irrigated systems (Table 1). This result is consistent with De Luis-Peralta *et al.* (2025), who found that irrigated crops exhibited higher profitability than rainfed crops. This convergence supports the robustness of the findings and confirms that access to irrigation is a pivotal factor in enhancing agricultural profitability.

Table 1.

Federal entity	Total area (ha)	Total production (t)	Production system	Area with competitiveness (ha)	Production with competitiveness (t)
Aguascalientes	4,415.00	66,559.50	TR (99%) - P	4,386.63	66,131.84
Baja California*	1.55	2.74	TR - P	1.05	1.85
Baja California Sur	18.50	91.07	TR - P	n.c.	n.c.
Campeche	76.36	92.80	TR - P	n.c.	n.c.
Coahuila	n.i.	n.i.	n.i.	n.i.	n.i.
Colima	49.60	376.78	TR - P	n.c.	n.c.
Chiapas	62.00	329.84	TR - P	n.c.	n.c.
Chihuahua	22.72	94.90	TR - P	n.c.	n.c.
Mexico City (CDMX)	1.91	1.19	TR - P	n.c.	n.c.
Durango	255.57	330.22	TR - P	n.c.	n.c.

Table 1. Continues...

Federal entity	Total area (ha)	Total production (t)	Production system	Area with competitiveness (ha)	Production with competitiveness (t)
Guanajuato*	119.00	961.85	TR - P	n.c.	n.c.
Guerrero*	221.58	2,406.07	TR - P	106.55	1,156.95
Hidalgo	64.00	433.80	TR - P	n.c.	n.c.
Jalisco	333.47	3,607.38	TR - P	136.39	1,475.39
State of Mexico*	845.50	9,217.38	TR - P	593.67	6,471.97
Michoacán	12,729.00	192,612.82	TR (98%) - P	12,490.28	189,000.53
Morelos	15.00	118.60	TR - P	n.c.	n.c.
Nayarit	36.00	311.85	TR - P	12.23	105.98
Nuevo León	1.05	0.11	TR - P	n.c.	n.c.
Oaxaca	236.61	1,415.39	TR - P	n.c.	n.c.
Puebla	47.30	444.00	TR - P	n.c.	n.c.
Querétaro	73.00	267.28	TR - P	n.c.	n.c.
Quintana Roo	20.72	55.96	TR - P	n.c.	n.c.
San Luis Potosí	110.30	193.34	TR - P	n.c.	n.c.
Sinaloa	3.00	15.99	TR - P	n.c.	n.c.
Sonora	n.i.	n.i.	n.i.	n.i.	n.i.
Tabasco*	18.00	218.88	TR - P	0.61	7.46
Tamaulipas	55.46	460.84	TR - P	n.c.	n.c.
Tlaxcala	4.15	0.12	TR - P	n.c.	n.c.
Veracruz*	13.50	96.26	TR - P	0.54	3.86
Yucatán*	10.00	135.00	T (91%) R - P	9.10	122.85
Zacatecas	1,505.00	23,824.02	TR (100%) - P	1,499.73	23,740.61

Source: Authors' elaboration.

*No social competitiveness. T=rainfed; R=irrigated; n.i.=no information; P=perennial; n.c.=no private competitiveness.

Mexico exhibited high private competitiveness in guava production, achieved across 19,292.48 ha, corresponding to 8,746 Guava Production Units (GPUs). However, this level of competitiveness was lower than the profitability indicator. In this regard, González and Alferes (2010) note that being profitable does not necessarily imply being competitive, which explains this discrepancy. In other words, competitiveness requires additional conditions such as efficiency, sustainability, and market persistence (Müller, 1995).

Profitability and competitiveness at efficiency prices

Public policy effects and market distortions altered realized profitability; therefore, assessing performance at efficiency prices made it possible to identify the system's underlying (true) profitability and competitiveness. National production was largely socially profitable (H); however, a substantial share of production units did not achieve social profitability due to low economic-efficiency metrics, resulting in structural differences across production systems. The loss of social profitability is mainly attributable to the small scale of many production units, which limits their capacity to expand output and, consequently, leads

to higher production costs. By contrast, large-scale production systems sustain high profitability due to superior infrastructure and integration into more dynamic markets, including international markets.

These results indicate that the lack of profitability primarily affects small guava producers, who face greater constraints in generating sufficient income and maintaining the economic viability of their production units. Consequently, incentivizing small agricultural producers is pivotal for sectoral development, as they supply food to more than 40% of Mexico's population (SADER, 2024). When competitiveness was evaluated at economic prices, national production showed a very high level of social competitiveness (280,454.73 t), harvested on 86.71% of the hectares devoted to this crop and generated by 27.35% of national GPUs. The gap between profitability and competitiveness estimated at economic prices underscores that a producer or system may be profitable in the short term, yet not necessarily competitive. The federal entities with the highest social competitiveness were Michoacán, Aguascalientes, and Zacatecas, followed though to a lesser extent by Jalisco and Nayarit. This difference may be explained by the greater participation of medium- and large-scale producers in the first three entities, which facilitates economies of scale, reduces unit costs, and expands access to financing.

Nominal and effective protection coefficients

The average (NPC) for outputs was 1.03 (Table 2), indicating that, as a result of agricultural policy, producers received prices 3% above the social value. This outcome reflects an implicit subsidy embedded in guava prices, providing producers with additional protection relative to the social benchmark. The NPC for tradable inputs indicates that market prices were below social prices, evidencing the presence of subsidies or an overvalued exchange rate that reduced their cost.

Table 2. Summary coefficients.

Crop	Nominal Protection Coefficient (NPC)	Effective Protection Coefficient (EPC)		Factor Cost Coefficient (FCC)
Guava	Output	Input		0.73
	1.03	0.94	1.05	

In 93.75% of state-level production systems, the (EPC) exceeded the Nominal Protection Coefficient (NPC), indicating that, in most states, agricultural policy is essential to sustaining guava production (45,504 t). This finding is consistent with Chica *et al.* (2016), who underscore the role of subsidies in enabling producers to remain in the market. Nevertheless, the results of the present study suggest that excessive reliance on such support may constrain long-term competitiveness, because factors such as productive efficiency and resource management are likewise decisive for sustaining profitability. By contrast, in Michoacán and Aguascalientes, agricultural policy was not determinative, as the NPC and EPC exhibited similar values. This pattern may be explained by the more consolidated infrastructure for collection, transport, and export channels in both states, together with a stronger orientation toward international markets

(Servicio Nacional de Sanidad, Inocuidad y Calidad Agroalimentaria [SENASICA], 2025), which is consistent with their high productivity (85% of national production). In this regard, Jaffee (1993) showed that such consolidation was the outcome of public policies targeting the agricultural sector, including government negotiations to access new markets and support to promote the product internationally. The results further indicate that maintaining a scheme of generalized subsidies may foster dependency on these transfers, directly affecting social prices.

Divergences and efficiency

The comparison between private and social profitability in guava production showed that profitability calculated at market prices exceeded that estimated at social prices. This result can be attributed to State transfers and market distortions, which increased private gains by 2.87% above the underlying economic profitability, indicating that public policy or market imperfections generated excess private benefits for producers. This, in turn, suggests the presence of subsidies or support mechanisms that incentivized the productive activity. Guava production exhibited a relative competitiveness of 1.03; however, this value was 0.17 below the private-social profitability comparison, suggesting that while the activity is attractive for investors, it may entail social losses or adverse societal effects. This discrepancy arises because competitive capacity is not homogeneous across states. Guanajuato, Guerrero, the State of Mexico, Tabasco, Veracruz, and Yucatán lack competitiveness under economic-efficiency conditions (Table 1), which may reflect structural constraints (high costs, low yields, small-scale production, among others).

However, only a limited number of states (Aguascalientes, Michoacán, and Zacatecas) displayed comparative advantages, as reflected in a domestic factor cost coefficient below one. This outcome is explained by the fact that most production (92.88%) is concentrated in states with consolidated productive conditions, irrigated systems, favorable soils, and higher levels of technification (SIAP, 2019), translating into better yields and greater productive efficiency. In this context, Von Hesse (1994) argued that public policies can stimulate competitiveness, particularly those designed to promote export dynamism. Structural differences between production schemes are also evident. Although public policy contributes to sustaining productive activity and the incomes of a large number of small producers, results at social prices indicate that not all producers achieved favorable performance, suggesting that these policies do not correct structural limitations in every state. These findings imply that some small-scale producers maintained benefits due to public policies or market conditions rather than genuine competitiveness. In this regard, Von Hesse (1994) proposes incorporating smallholders into international markets as a strategy to strengthen real competitiveness over the long term. Thus, even when small producers obtain profits, society as a whole may face inefficient resource use, distortions in capital allocation, and, in some cases, additional environmental or fiscal costs. Porter (2007) notes that governments often prioritize policies with immediate benefits such as subsidies and protections which can constrain innovation and sectoral competitiveness. Overall, the results indicate that guava production in Mexico is profitable and competitive at private prices; however, at social prices, these indicators decline, revealing distortions

associated with agricultural policy. Protection coefficients show that private profitability exceeds social profitability, reflecting dependence on prevailing protection mechanisms.

CONCLUSIONS

Guava production in Mexico exhibited high levels of private and social profitability and competitiveness. However, relative competitiveness was slightly lower than the private-social profitability comparison. National production showed comparative advantages concentrated in two states, revealing substantial regional differences in efficiency and competitive potential. In lower-performing regions, it is necessary to emphasize the implementation of regional strategies that strengthen efficiency and competitiveness. Agricultural public policies increased the profitability and competitiveness of guava production in Mexico. Nonetheless, it is essential to adopt strategies that consolidate sustained competitiveness in the medium and long term, rather than focusing exclusively on immediate outcomes. The Effective Protection Coefficient was the most sensitive indicator of public policy intervention, as it comprehensively captured distortions in input and output markets. The principal contribution of the Policy Analysis Matrix in this study lies in identifying areas of opportunity where the State can intervene through agricultural policy instruments, such as regional targeting and the design of differentiated strategies aligned with the needs of each state. In addition, applying this methodology to other crops is recommended, including fruit crops, horticultural crops, livestock systems, and staple grains.

REFERENCES

- Chica, J., Tirado, Y. C., & Barreto, J. M. (2016). Indicadores de competitividad del cultivo del arroz en Colombia y Estados Unidos. *Revista de Ciencias Agrícolas*, 33(2), 16-31. <https://doi.org/10.22267/rcia.163302.49>
- Comisión Nacional de los Salarios Mínimos. (2023). Se publican en el Diario Oficial de la Federación los salarios mínimos vigentes a partir del 1 de enero de 2024. <https://www.gob.mx/conasami/es/articulos/se-publican-en-el-diario-oficial-de-la-federacion-los-salarios-minimos-vigentes-a-partir-del-1-de-enero-de-2024>
- De Luis-Peralta, A., Vega-Valdivia, D. D., Garza-Bueno, L. E., & Barrios-Puente, G. (2025). Análisis de la política agrícola en México: Rentabilidad, competitividad y autosuficiencia alimentaria en granos básicos. *Agricultura, Sociedad y Desarrollo*, 22(1), 107-122. <https://doi.org/10.22231/asvd.v22i1.1693>
- González, A., & Alferes, M. (2010). Competitividad y ventajas comparativas de la producción de maíz en México. *Revista Mexicana de Ciencias Agrícolas*, 1(3), 381-396. <https://www.scielo.org.mx/pdf/remexca/v1n3/v1n3a8.pdf>
- González, A., & Orrantia, M. A. (2006). Los subsidios agrícolas de México. *Agricultura Técnica en México*, 32(3), 323-331. <https://www.scielo.org.mx/pdf/agritm/v32n3/v32n3a8.pdf>
- Instituto Nacional de Estadística y Geografía. (2024). Censo Agropecuario (CA) 2022. Recuperado el 16 de abril de 2025, de <https://www.inegi.org.mx/programas/ca/2022/#tabulados>
- Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. (2018). Variedades de guayabo con potencial productivo en Nayarit. <https://www.gob.mx/inifap/prensa/variedades-de-guayabo-con-potencial-productivo-en-nayarit>
- Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. (2025). Agendas tecnológicas. <https://www.gob.mx/inifap/acciones-y-programas/agendas-tecnologicas>
- Jaffee, S., & Gordon, P. (1993). Exporting high-value food commodities: Success stories from developing countries (No. 198). World Bank Publications.
- Monke, E. A., & Pearson, S. R. (1989). The policy analysis matrix for agricultural development: A manual for practitioners. The Praga Corporation.
- Müller, G. (1995). El caleidoscopio de la competitividad. *Revista de la CEPAL*, 56, 137-148. <https://hdl.handle.net/11362/11993>

- Organización de las Naciones Unidas para la Agricultura y la Alimentación. (2000). Las negociaciones comerciales multilaterales sobre la agricultura: Los instrumentos de protección y sus repercusiones económicas. <https://www.fao.org/4/x7352s/X7352s00.htm>
- Porter, M. (2007). La ventaja competitiva de las naciones. *Harvard Business Review*, 85(11), 69-95.
- Porter, M. E. (2016). Ventaja competitiva: Creación y sostenimiento de un desempeño superior. Grupo Editorial Patria.
- Programa de las Naciones Unidas para el Desarrollo. (2018). Competitividad social en México. <https://www.undp.org/es/latin-america/publicaciones/competitividad-social-en-mexico>
- Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. (2007). Análisis integral del gasto público agropecuario en México. <https://www.agricultura.gob.mx/sites/default/files/sagarpa/document/2019/01/28/1608/01022019-analisis-integral-del-gasto-publico-agropecuariao-en-mexico.pdf>
- Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. (2019). Metodología de la medición de competitividad de sistemas producto. Recuperado el 4 de abril de 2025, de <https://www.agricultura.gob.mx/sites/default/files/sagarpa/document/2019/01/28/1608/01022019-metodologia-de-la-medicion-de-competitividad-de>
- Secretaría de Agricultura y Desarrollo Rural. (2019). La guayaba, poderosa y sabrosa. Recuperado el 17 de junio de 2025, de <https://www.gob.mx/agricultura/articulos/la-guayaba-poderosa-y-sabrosa>
- Secretaría de Agricultura y Desarrollo Rural. (2023). Acciones para mejorar los rendimientos agrícolas. <https://www.gob.mx/agricultura/articulos/acciones-para-mejorar-los-rendimientos-agricolas>
- Secretaría de Agricultura y Desarrollo Rural. (2024). Productores de pequeña escala, garantes de la agrobiodiversidad y principales proveedores de alimentos del país. <https://www.gob.mx/agricultura/prensa/productores-de-pequena-escala-garantes-de-la-agrobiodiversidad-y-principales-proveedores-de-alimentos-del-pais>
- Secretaría de Hacienda y Crédito Público. (2023). Catálogos para la emisión de CFDI con complemento para comercio exterior versión 1.1. http://omawww.sat.gob.mx/tramitesyservicios/Paginas/catalogos_emision_cfdi_complemento_ce.htm
- Secretaría de Hacienda y Crédito Público. (2025). Cuenta pública 2024. <https://www.cuentapublica.hacienda.gob.mx/work/models/CP/2024/tomo/I/I50.06.PEF.pdf>
- Servicio de Información Agroalimentaria y Pesquera. (2019). El poder de la guayaba. <https://www.gob.mx/siap/articulos/el-poder-de-la-guayaba>
- Servicio de Información Agroalimentaria y Pesquera. (2024). Panorama agroalimentario 2018-2024. <https://www.gob.mx/agricultura/dgsiap/acciones-y-programas/panorama-agroalimentario-258035>
- Servicio de Información Agroalimentaria y Pesquera. (2025). Anuario estadístico de la producción agrícola. https://nube.agricultura.gob.mx/cierre_agricola/
- Servicio Nacional de Información de Comercio Exterior. (2025). SIAVI Data. <http://187.217.44.135/eid/web/preclasificadorexterno>
- Servicio Nacional de Sanidad, Inocuidad y Calidad Agroalimentaria. (2025). Huertos de guayaba registrados para exportación a los Estados Unidos de América. <https://www.gob.mx/senasica/documentos/huertos-de-guayaba-registrados-para-exportacion-a-los-estados-unidos-de-america>
- Von Hesse, M. (1994). Políticas públicas y competitividad de las exportaciones agrícolas. *Revista de la CEPAL*, 53, 129-146. <https://www.cepal.org/es/publicaciones/11954-politicas-publicas-competitividad-exportaciones-agricolas>
- Wenqi, D., Khurshid, A., Rauf, A., & Calin, A. C. (2022). Government subsidies' influence on corporate social responsibility of private firms in a competitive environment. *Journal of Innovation & Knowledge*, 7(2). <https://doi.org/10.1016/j.jik.2022.100189>