

# Agrociencia

ISSN: 2521-9766

VOLUME 58, NUMBER 5 | JULY 1 - AUGUST 15, 2024 | MEXICO



SECRETARÍA DE AGRICULTURA

## EDITORIAL TEAM

### EDITOR IN CHIEF, AGROCIENCIA

Fernando Carlos Gómez Merino

### DEPUTY EDITOR, AGROCIENCIA

Libia Iris Trejo-Téllez

### INTERNATIONAL

#### EDITORIAL COUNCIL

Roger Austin (UK)

José Sarukhán Kermez (Mexico)

Barry C. Arnold (USA)

### INTERNAL EDITORIAL ADVISORY

#### COMMITTEE

Jorge Alvarado López

Jorge D. Etchevers Barra

Víctor A. González Hernández

Said Infante Gil

Leopoldo E. Mendoza Onofre

José A. Villaseñor Alva

### RESPONSIBLES OF THE EDITION

Fernando Carlos Gómez Merino

### DESIGN AND COMPOSITION

L. Brenda Espejel Lagunas

### TRANSLATORS

Inés Enriquez

Joel Castillo González

Nicolas Crossa

### METADATA HARVESTER

Moises Quintana Arévalo

### PLATFORM SUPPORT

L. Brenda Espejel Lagunas

Valeria Abigail Martínez Sias

Ana Luisa Mejía Sandoval

### SECRETARIAL ASSISTANCE

Yolanda Feroso Meraz

COPYRIGHT AND RELATED RIGHTS, **Volume 58, Number 5, July 01 - August 15, 2024**, Agrociencia is a semi-monthly publication edited by Colegio de Postgraduados. Carretera Mexico-Texcoco, Km 36.5, Montecillo, Texcoco, State of Mexico. CP 56264. Phone: 5959284427. [www.colpos.mx](http://www.colpos.mx). Editor in chief: Dr. Fernando Carlos Gómez Merino. Reservations of Rights to Exclusive Use 04-2021-031913431800-203. eISSN: 2521-9766, granted by the National Copyright Institute. Last modification date, **August 15, 2024**.

The opinions expressed by the authors do not necessarily reflect the position of the editor of the publication.

All correspondence (subscription information, sales, advertising, author contributions, etc.) should be addressed to:

Central Office:

#### AGROCIENCIA

Guerrero #9, Esquina Avenida Hidalgo.

56220. San Luis Huexotla. Texcoco,

State of Mexico

Phone: 595 92 84427

<https://agrociencia-colpos.org/index.php/agrociencia>

**DISCLAIMER:** Trade marks or any commercial representations cited on scientific articles, essays or notes do not imply nor should be inferred as Agrociencia endorsement. No criticism, disclosure or rejection should be assumed either. Likewise, statements or recommendations expressed by authors are solely their responsibility and may not totally agree with those of the Editor.

**Cover:** Cafeticultura mexicana

**Photography and credits:** Adán Villa Herrera



# AGRICULTURA

SECRETARÍA DE AGRICULTURA Y DESARROLLO RURAL

## CROP SCIENCE

GLUTENIN DIVERSITY OF FLOUR WHEAT (*Triticum aestivum* L.)  
FOR COOKIE QUALITY IN MEXICO

533

Eduardo **Espitia-Rangel**, Eliel **Martínez-Cruz**, Héctor Eduardo **Villaseñor-Mir**,  
Julio **Huerta-Espino**, René **Hortelano-Santa Rosa**VEGETATIVE GROWTH OF PEACH TREES [*Prunus persica* (L.) Batsch]  
ASSOCIATED WITH NATIVE SQUASH (*Cucurbita pepo* ssp. *pepo* L.)  
AND BAYOCOTE (*Phaseolus coccineus* L.) IN MILPA  
INTERCROPPED WITH FRUIT TREES (MIAF) SYSTEMS

543

Eduardo **Muñoz-Ruiz**, Horacio **Santiago-Mejía**, Ildefonso **Ronquillo-Cedillo**,  
Rocio **Albino-Garduño**, José Isabel **Cortés-Flores**, Julie **Grossman**

## FOOD SCIENCE

POST-HARVEST PRACTICES FOR THE PRODUCTION OF  
SPECIALTY COFFEES IN CHIAPAS, MEXICO

557

Eztli Itzel **Morales-Reyes**, Martín Alejandro **Bolaños-González**,  
**Esteban** Escamilla-Prado, Antoine **Libert-Amico**

## NATURAL RENEWABLE RESOURCES

ORCHID DIVERSITY (Orchidaceae) IN TWO URBAN SITES  
IN THE STATE OF VERACRUZ, MEXICO

571

Obdulia **Baltazar-Bernal**, Jesús **Zavala-Ruiz**, Arturo **Hernández-García**

PLANT PROTECTION

SPATIAL ANALYSIS OF ANTHRACNOSE IN AVOCADO  
(*Persea americana* Mill.) IN DONATO GUERRA, MEXICO

584

Atenas **Tapia-Rodríguez**, José Francisco **Ramírez-Dávila**, Alfredo **Ruiz-Orta**,  
Dulce Karen **Figuroa-Figuroa**, Agustín David **Acosta-Guadarrama**

SOCIOECONOMICS

PRODUCTION AND EXPORT OF BERRIES IN MEXICO'S AGRICULTURAL  
DEVELOPMENT: A STUDY OF COMPETITIVE ADVANTAGE

595

Jesús Ernesto **Rocha-Ibarra**, Ana Isabel **Mireles-Arriaga**,  
Jorge Eric **Ruiz-Nieto**, Griselda **Maki-Díaz**

RICE (*Oryza sativa* L.) SELF-SUFFICIENCY IN MEXICO:  
IS IT POSSIBLE TO ACHIEVE IT?

609

Jenny **Virgilio-León**, José Alberto **García-Salazar**, Saturnino **Mora-Flores**,  
Roberto **García-Mata**, Rocío **Ramírez-Jaspeado**

WATER-SOIL-CLIMATE

TEMPERATURE AND PRECIPITATION TRENDS DUE TO CLIMATE  
CHANGE IN THE HUIXTLA RIVER BASIN IN CHIAPAS, MEXICO

627

Ricardo **Álvarez-López**, Laura Alicia **Ibáñez-Castillo**,  
Mario Alberto **Vázquez-Peña**, Agustín **Ruiz-García**

VEGETATIVE COVER OF A MINE TAILINGS WITH BERMUDA GRASS  
(*Cynodon dactylon* L.) TO MITIGATE POLLUTION

641

Elizabeth **Hernández-Acosta**, Emma Ángela **Acevedo-Girón**,  
Edmundo **Robledo-Santoyo**, Jorge Luis **Castrellón-Montelongo**

## GLUTENIN DIVERSITY OF FLOUR WHEAT (*Triticum aestivum* L.) FOR COOKIE QUALITY IN MEXICO

Eduardo Espitia-Rangel<sup>1</sup>, Eliel Martínez-Cruz<sup>1\*</sup>, Héctor Eduardo Villaseñor-Mir<sup>1</sup>,  
Julio Huerta-Espino<sup>1</sup>, René Hortelano-Santa Rosa<sup>1</sup>

<sup>1</sup>Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Campo Experimental Valle de México. Chapingo, Texcoco, State of Mexico, Mexico. C. P. 56230.

\* Author for correspondence: martinez.eliel@inifap.gob.mx

### ABSTRACT

Glutenins are high- and low-molecular-weight proteins (HMW-G and LMW-G). They play a determining role in genetic improvement to define industrial quality in flour wheat, so understanding their variability is necessary for directing selection toward a specific quality. The objective of this research was to determine the diversity of HMW-G and LMW-G alleles of genotypes from the flour wheat breeding program of the National Institute of Forestry, Agricultural, and Livestock Research (INIFAP) useful for cookie quality. Twenty-five genotypes were used, including six Mexican cookie varieties, as well as 21 genotypes introduced from an international collection of accessions from the International Maize and Wheat Improvement Center (CIMMYT). HMW-G and LMW-G were identified based on their separation on polyacrylamide gels in the presence of sodium dodecyl sulfate. For HMW-G, the 2\* variant in *Glu-A1* was the most frequent variant for the trial and introduction nursery, with more than 80 %. At the *Glu-B1* locus, the 7+9 and 7 variants were the most frequent, with 60 and 38.1 % in trial and nursery, respectively. For *Glu-D1*, the 2+12 variant was the most frequent in the trial with 64 %, and 5+10 with 85.7 % in nursery. The latter allele favors baking quality. For the *Glu-A1* and *Glu-D1* loci, it is necessary to introduce genotypes with null alleles or with the 2+12<sub>1</sub> variant in *Glu-D1* associated with cookie quality. For the highest-frequency variants of LMW-G, c in *Glu-A3*, h in *Glu-B3*, and b in *Glu-D3* are associated with baking quality. With the aforementioned, it is concluded that there is a low frequency and little variation in useful alleles of HMW-G and LMW-G for cookie quality in the introduced accessions analyzed, implying that new genetic sources that favor it should be explored.

**Keywords:** proteins, high and low molecular weight glutenins, breeding.

### INTRODUCTION

Within the objectives of flour wheat (*Triticum aestivum* L.) breeding, it is necessary to combine variety traits with higher yield potential, disease tolerance, and qualities for a specific industrial use (Kiszonas and Morris, 2018). Within the flour wheat breeding program, there is selection for a better cracker factor, which combines larger diameter and smaller cracker thickness, which is a way of indicating its quality (Ma *et al.*, 2020;

**Citation:** Espitia-Rangel E, Martínez-Cruz E, Villaseñor-Mir HE, Huerta-Espino J, Hortelano-Santa Rosa R. 2024. Glutenin diversity of flour wheat (*Triticum aestivum* L.) for cookie quality in Mexico. *Agrociencia* 58(5): 533-542. <https://doi.org/10.47163/agrociencia.v58i5.2962>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: July 13, 2022.  
Approved: March 14, 2024.  
**Published in Agrociencia:**  
July 16, 2024.

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



Zhang *et al.*, 2020). This variable is commercially expressed as producing more cookies per unit of flour used in their production.

One of the main components that define the cookie factor are flour proteins called glutenins. This protein, along with gliadins, forms gluten, which is an insoluble polymer in the presence of water that gives the dough the characteristics of strength, tenacity, extensibility, and viscosity, which partially defines the industrial use of flour wheat genotypes as suitable for cookie or bakery use (Zhang *et al.*, 2023).

Glutenins are classified as high- and low-molecular-weight glutenins (HMW-G and LMW-G) based on their separation on polyacrylamide gels in the presence of sodium dodecyl sulfate as a reducing agent. The *Glu-A1*, *Glu-B1*, and *Glu-D1* loci code for HMW-G subunits (Payne and Lawrence, 1983), and LMW-G is encoded by the *Glu-A3*, *Glu-B3*, and *Glu-D3* loci (Singh and Shepherd, 1988). Through genetic recombination, combinations of HMW-G and LMW-G alleles can be generated for bakery and cookie making. These qualities differ because bread requires strong doughs to increase its volume, whereas cookies require weak doughs that favor cookie diameter (Sarkar *et al.*, 2015).

Research has identified the alleles and their combinations that favor cookie quality. In this context, it has been reported that the HMW-G combinations associated with higher cookie factor are: the absence of subunit (null allele) in *Glu-A1*, the presence of the 7+8 allele in *Glu-B1*, as well as the 2+12 or null allele in *Glu-D1* (Zhang *et al.*, 2018; Ma *et al.*, 2019). A new allelic variant in *Glu-D1* called 2+12<sub>1</sub> was also identified and associated with the biscuit expansion (Ma *et al.*, 2020). In addition, Sharma *et al.* (2021), Zhang *et al.* (2018), and Ma *et al.* (2020) proposed the *Glu-A1*, *Glu-B1*, and *Glu-D1* combinations of HMW-G: 2\*, 7, 2+12; 0, 7+8, 0, and 1, 7+8, 2+12<sub>1</sub>, associated with larger cookie diameter.

In Mexico, there are several studies in flour wheat that have identified HMW-G and LMW-G alleles and their best combinations of with the aim of favoring baking quality (Hernández-Espinosa *et al.*, 2013; Martínez-Cruz *et al.*, 2014; Muñoz-Calixto *et al.*, 2022). However, there is a lack of assessment to identify variants and their combinations that benefit cookie quality. An important condition for selection in a breeding program is to know the existing genetic variability in order to derive progenies with the desired characteristics. The National Institute of Forestry, Agricultural, and Livestock Research (INIFAP) wheat breeding program consists of genotypes with HMW-G and LMW-G alleles associated with excellent cookie quality. The present research aimed to know the diversity of these alleles in the genotypes of the program and to identify those useful for cookie quality.

## MATERIALS AND METHODS

### Plant material and field evaluation

Two groups of genotypes from the INIFAP breeding program were used. The group called the Fifth National Soft Wheat Trial (5th ENSUVES) consisted of 25 genotypes,

of which seven were commercial varieties (Cortázar S94, Bárcenas S2002, Maya S2007, Urbina S2007, Torocahui S2008, Borlaug 100 F2014, and Faisán S2016) and 18 were advanced  $F_6$  lines generated by the breeding programs of INIFAP and the International Maize and Wheat Improvement Center (CIMMYT). Varieties with a letter “S” in their name were released by INIFAP for use in the cookie industry in Mexico, indicating their soft dough is suitable for cookie production, while the number refers to the year of release. The Borlaug 100 F2014 variety was used as a reference control because of its high yield in irrigated areas, which is representative of strong dough varieties for baking. A second group consisted of 21  $F_6$  lines generated in 2019 for CIMMYT international evaluation trials and introduced by INIFAP with the aim of identifying new genetic sources to increase the variability of alleles associated with higher cookie quality.

Planting took place in the 2019–2020 autumn–winter cycle at INIFAP’s Bajío Experimental Field (CEBAJ) in Celaya, Guanajuato, Mexico. The experimental design was a randomized complete block design with two replications. The experimental unit consisted of four 3 m-long furrows with a spacing of 30 cm and a sowing density of 120 kg ha<sup>-1</sup>. Sowing took place in the first week of December under irrigated conditions. The fertilizer rate of 240-60-00 was used; half of the N and all of the P<sub>2</sub>O<sub>5</sub> were applied at sowing, and the rest of the N was applied with the first relief irrigation. Fertilizer sources were urea with 46 % N [CO (NH<sub>2</sub>)<sub>2</sub>] and triple calcium superphosphate with 46 % P<sub>2</sub>O<sub>5</sub> [Ca (H<sub>2</sub>PO<sub>4</sub>)<sub>2</sub>]. Narrow-leaved weeds were controlled with an application of Topik® 240 EC (clodinafop-propargyl + cloquintocet-mexyl) 30 days after sowing irrigation, and broad-leaved weeds with Esteron® 47 EC (2-4-dichlorophenoxyacetic acid) 35 days after emergence. An application of 2.5 % cypermethrin® (C<sub>22</sub>H<sub>19</sub>C<sub>12</sub>NO<sub>3</sub>) was made for aphid control at the grain formation and filling stages.

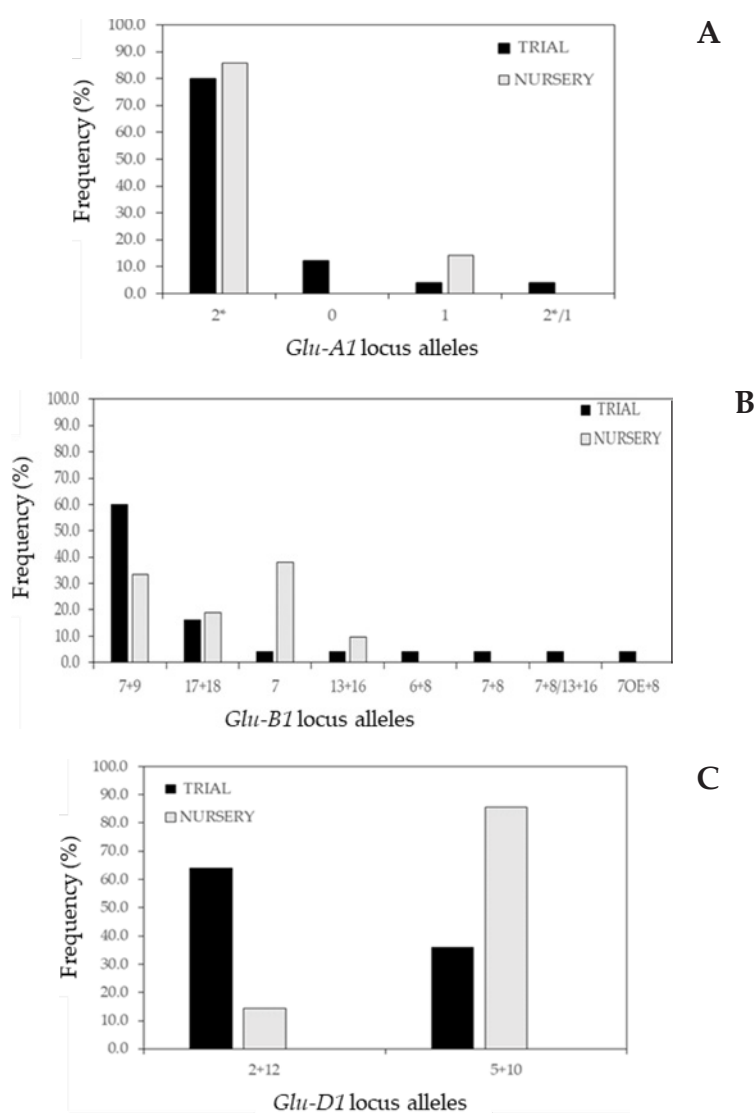
#### Laboratory analysis and information

One ear from each plot was collected and threshed for the extraction of HMW-G and LMW-G. The grains from each ear were milled in a UDY-type mill, and the electrophoretic analysis of glutenins was performed using the method of Guzmán *et al.* (2022) at the Cereal Chemistry and Quality Laboratory of CIMMYT. Separation of the protein subunits was obtained from a 40 mg sample of wholemeal flour using 14 % acrylamide gels at pH 8.5, applying 9 mA per gel for 17 h. The HMW-Gs (loci *Glu-A1*, *Glu-B1*, and *Glu-D1*) were identified based on the nomenclature proposed by Payne and Lawrence (1983), and the LMW-Gs (loci *Glu-A3* and *Glu-B3*) according to Singh *et al.* (1991), Jackson *et al.* (1996), and Branlard *et al.* (2003). For the *Glu-D3* locus, the nomenclature proposed by Branlard *et al.* (2003) was used.

For each group of genotypes, allele frequencies were calculated for the *Glu-A1*, *Glu-B1*, and *Glu-D1* loci coding for the HMW-Gs, as well as for the *Glu-A3*, *Glu-B3*, and *Glu-D3* loci of the LMW-Gs. All HMW-G and LMW-G allele combinations were identified for each of the genotypes.

## RESULTS AND DISCUSSION

The frequency of allelic variants coding for HMW-Gs for both groups of lines analyzed (Figure 1) shows that, for the *Glu-A1* locus, allelic variants 2\*, 0, and 1 and the heterologous allele 2\*/1 were identified in the trial, while for the lines introduced from the nursery, alleles 2\* and 1 were identified. Variant 2\* was the most frequent variant in the trial and introduction nursery, with more than 80 %, so new lines should be evaluated to favor the presence of the 0 allele, which is associated with higher cookie quality (Zhang *et al.*, 2012).



**Figure 1.** Allelic variants of the loci coding for HMW-Gs of flour wheat (*Triticum aestivum* L.) genotypes from the breeding program of the National Institute of Forestry, Agricultural, and Livestock Research (INIFAP). A: *Glu-A1*; B: *Glu-B1*; C: *Glu-D1*.

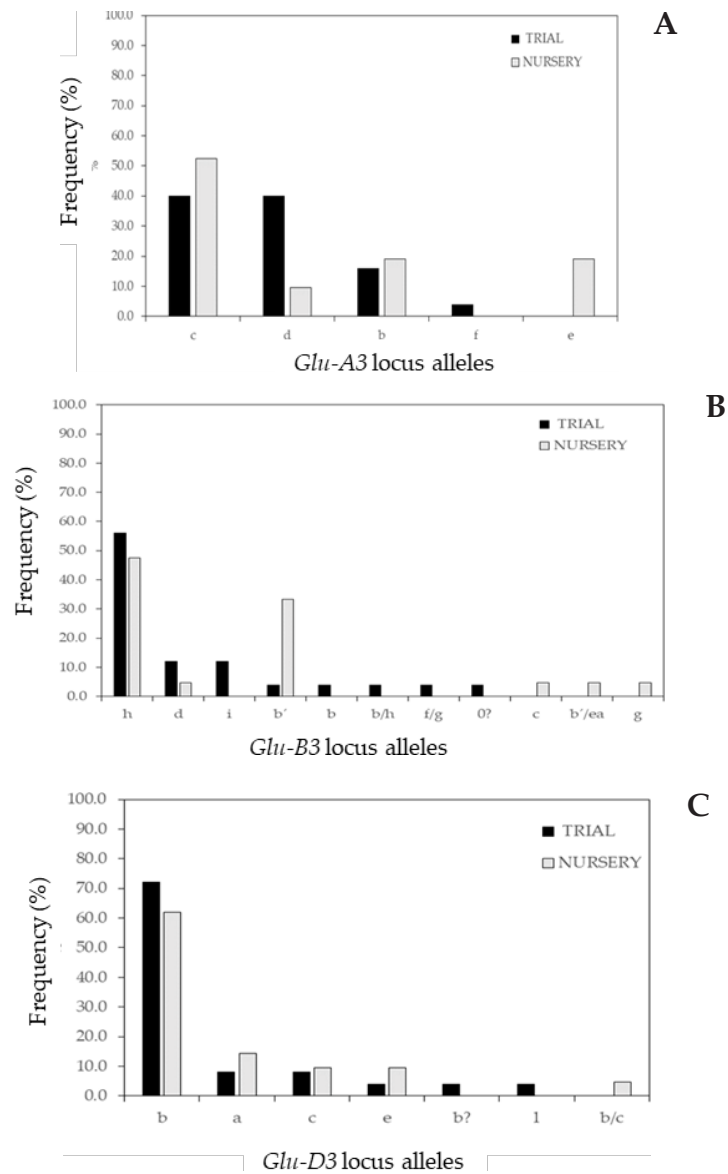
At the *Glu-B1* locus, seven allelic variants (7+9, 17+18, 7, 13+16, 6+8, 7+8, and 7OE+8) and one heterologous allele (7+8/13+16) were found in the trial, and 7+9, 17+18, 7, and 13+16 alleles were identified in the nursery. For this locus, the highest frequency variants in the trial were 7+9 and 17+18, with 60 and 16 %, respectively. For the introduction nursery, they were 7, 7+9, and 17+18, with values of 38.1, 33.3, and 19 %, respectively. According to Moiraghi *et al.* (2013), allele 7 is suitable for cookie fitness, so these genotypes should be selected.

For the *Glu-D1* locus, the 2+12 and 5+10 alleles were identified. The 2+12 variant was the most frequent in the trial (64 %), while 5+10 was the most frequent for the introduction nursery (85.7 %). This is partly due to the fact that the national trial included the varieties Cortázar S94, Bárcenas S2002, Maya S2007, Urbina S2007, Torocahui S2008, and Faisán S2016, which had the 2+12 allele and were released for use in the cookie industry. Zhang *et al.* (2018) and Ma *et al.* (2019) mentioned that zero or null alleles in *Glu-A1*, 7 and 7+8 in *Glu-B1*, and 2+12 in *Glu-D1* favor cookie quality, so it is necessary to maintain genotypes containing these alleles and continue exploring genotypes to introduce a greater number of lines with these variants. Likewise, according to Ma *et al.* (2020), it is imperative to introduce materials with the 0 and 2+12<sub>1</sub> variants in *Glu-D1*, which favor the cookie factor, to reduce the presence of the 5+10 allele, which is associated with higher baking quality (Guzmán *et al.*, 2022), as is the case of the control variety Borlaug 100 F2014.

Regarding the frequency of alleles coding for the LMW-G (Figure 2), for the *Glu-A3* locus, variants c, d, and b were common between the trial and the introduction nursery, while f occurred in the trial and e in the nursery. Variants c and d were the most frequent variants (40 %) in the trial, while c (52 %), b (19 %), and e (19 %) were the most frequent in the introduced lines. At the *Glu-B3* locus, 11 allelic variants were identified, which corresponds to the highest number of all loci analyzed. The highest frequency variants were h (56 %), d (12 %), and i (12 %), respectively, for the test lines. In the case of the h allele, it was again found most frequently (47.7 %) in the nursery lines; the second most frequent was the b' variant (33.3 %).

Six alleles in *Glu-D3* and one heterologous allele (b/c) were identified. The most frequent alleles for the trial and nursery were b, a, and c, with b accounting for more than 60 % in both groups of lines. The most frequent alleles were c in *Glu-A3*, d and h in *Glu-B3*, as well as b in *Glu-D3* in both groups of lines. According to Zhang *et al.* (2012) and Wang *et al.* (2016), these alleles were associated with higher sedimentation volume and resistance in the extensograph, which favors baking quality. However, in the introduction nursery, the e and h variants in *Glu-A3* and *Glu-B3*, which decrease dough strength (Zhang *et al.*, 2012; Bonafede *et al.*, 2015; Franaszek and Salmanowicz, 2021) and may favor cookie quality, were identified in low frequency. Therefore, it is recommended to increase their frequency by introducing new genetic material.

According to Moiraghi *et al.* (2013) and Zhang *et al.* (2018), the combinations of HMW-Gs in *Glu-A1*, *Glu-B1*, and *Glu-D1* that favored the cookie factor were: 0, 7+8, and 2+12; 1, 7+8, and 0; and 0, 7+8, and 0, respectively. Within the group of lines of the national



**Figure 2.** Allelic variants of the loci coding for LMW-Gs of flour wheat (*Triticum aestivum* L.) genotypes from the breeding program of the National Institute of Forestry, Agricultural, and Livestock Research (INIFAP). A: *Glu-A3*; B: *Glu-B3*; C: *Glu-D3*.

trial, the genotype Maya S2007 and lines 1, 11, and 12 (Table 1) were identified as genetic sources for the genetic improvement of the cookie quality as they present at least two desirable alleles: 0 in *Glu-A1*, 7+8 in *Glu-B1*, and 2+12 in *Glu-D1*. On the other hand, lines 16, 19, 20, and 21 from the introduction nursery showed allele 7 in *Glu-B3* and alleles e and c of the *Glu-A3* and *Glu-B3* loci in LMW-G, respectively, which are

**Table 1.** Combinations of high and low molecular weight glutenins (HMW-G and LMW-G) of flour wheat (*Triticum aestivum* L.) genotypes from the National Soft Wheat Trial of the breeding program at the National Institute of Forestry, Agricultural, and Livestock Research (INIFAP).

	HMW-G			LMW-G		
	<i>Glu-A1</i>	<i>Glu-B1</i>	<i>Glu-D1</i>	<i>Glu-A3</i>	<i>Glu-B3</i>	<i>Glu-D3</i>
Maya S2007	0	6+8	2+12	f	null	B
Line 1	0	7+9	2+12	d	i	B
Line 11	0	7+9	2+12	d	i	B
Urbina S2007	1	13+16	2+12	b	d	B
Torocahui S2008	2*	7+9	2+12	c	h	E
Cortazar S94	2*	7+9	2+12	d	h	B
Bárceñas S2002	2*	7+9	2+12	c	H	b?
Line 4	2*	7+9	2+12	b	H	L
Line 6	2*	17+18	2+12	c	f, g	B
Line 7	2*	17+18	2+12	d	h	B
Line 8	2*	7+9	2+12	c	h	B
Line 12	2*	7+8	2+12	d	h	B
Line 13	2*	7+9	2+12	d	h	B
Line 15	2*	7+9	2+12	d	i	B
Line 16	2*	7+9	2+12	b	h	C
Faisán S2016	2*/1	7+8/13+16	2+12	d	b/h	B
Borlaug 100 F2014	2*	7	5+10	c	h	C
Line 2	2*	7OE+8	5+10	c	h	B
Line 3	2*	7+9	5+10	c	h	A
Line 5	2*	7+9	5+10	c	h	B
Line 9	2*	17+18	5+10	d	b`	B
Line 10	2*	7+9	5+10	c	h	A
Line 14	2*	17+18	5+10	d	b	B
Line 17	2*	7+9	5+10	b	d	B
Line 18	2*	7+9	5+10	c	d	B

associated with lower dough strength and may favor cookie quality, so these lines should be selected (Table 2).

It was not possible to identify the desirable combination for higher cookie quality of HMW-G (0, 7+18, 2+12) or LMW-G (e and c) within the genotypes analyzed, with the Maya S2007 variety being the genotype that presented the highest number of desirable alleles for HMW-G. For LMW-G, the desirable alleles e for *Glu-A3* and c for *Glu-D3* were not matched by any genotype.

According to Bonafede *et al.* (2015), it is important to note the difficulty in the individual identification of LMW-Gs on rheological quality and cookie or baking quality due to the linkage between the *Glu-3* and *Gli-1* loci. However, Ibba *et al.* (2017) indicate that there are different relationships between alleles of the *Glu-A3*, *Glu-B3*, and *Glu-D3* loci on cookie diameter. With some lines identified in the trial and introduction nursery, it will be possible to create combinations of HMW-G and LMW-G that favor cookie

**Table 2.** Combinations of high and low molecular weight glutenins (HMW-G and LMW-G) of flour wheat (*Triticum aestivum* L.) genotypes from the International Maize and Wheat Improvement Center (CIMMYT) introduction nursery.

	HMW-G			LMW-G		
	<i>Glu-A1</i>	<i>Glu-B1</i>	<i>Glu-D1</i>	<i>Glu-A3</i>	<i>Glu-B3</i>	<i>Glu-D3</i>
Line 17	2*	13+16	2+12	b	b	E
Line 12	2*	17+18	2+12	c	h	B
Line 10	2*	7+9	2+12	c	h	C
Line 5	2*	7	5+10	d	b'	B
Line 6	2*	7	5+10	c	b'/ea	E
Line 8	2*	7	5+10	b	b	B
Line 15	2*	7	5+10	c	b'	B
Line 16	2*	7	5+10	e	b'	B
Line 19	2*	7	5+10	e	h	A
Line 20	2*	7	5+10	e	h	B
Line 21	2*	7	5+10	e	h	A
Line 18	1	13+16	5+10	c	h	B
Line 11	2*	17+18	5+10	c	h	B
Line 13	2*	17+18	5+10	c	b'	B
Line 14	2*	17+18	5+10	c	b'	B
Line 3	1	7+9	5+10	c	g	B
Line 4	1	7+9	5+10	d	c	B
Line 1	2*	7+9	5+10	b	d	B
Line 2	2*	7+9	5+10	b	h	b/c
Line 7	2*	7+9	5+10	c	h	A
Line 9	2*	7+9	5+10	c	h	C

quality. Through genetic recombination of the variety Maya S2007 and lines 16, 19, 20, 21, and 4, glutenin combinations associated with higher cookie quality can be generated.

### CONCLUSIONS

The flour wheat germplasm in Mexico contains high-molecular-weight glutenin alleles 0 in *Glu-A1*, 7+8 in *Glu-B1*, and 2+12 in *Glu-D1*, as well as low-molecular-weight glutenin alleles e in *Glu-A3* and c in *Glu-B3*, in lines introduced from the International Maize and Wheat Improvement Center, which can favor cookie quality; however, their frequency is very low and dispersed. There is a need to introduce genetic sources that increase their frequency and diversity. It is recommended to introduce the 0 and 2+12<sub>1</sub> variants of the *Glu-D1* locus, which are associated with a larger cookie diameter. The use of genotypes with these variants and their genetic recombination will make it possible to obtain a greater accumulation of alleles to obtain lines with greater cookie aptitude.

## ACKNOWLEDGMENTS

To Mondelēz International, Inc. for partial funding of this research through the project Generation of Soft Wheat Varieties for Cookies in Mexico and to INIFAP for the project National Breeding Program to generate rust-resistant, high-yielding, and high-quality varieties for sustainable wheat production in Mexico.

## REFERENCES

- Bonafede MD, Tranquilli G, Pflüger LA, Peña RJ, Dubcovsky J. 2015. Effect of allelic variation at the *Glu-3/Gli-1* loci on breadmaking quality parameters in hexaploid wheat (*Triticum aestivum* L.). *Journal of Cereal Science* 62: 143–150. <https://doi.org/10.1016/j.jcs.2015.02.001>
- Branlard G, Dardevet M, Amieur N, Igrejas G. 2003. Allelic diversity of HMW and LMW glutenin subunits and omega-gliadins in French bread wheat (*Triticum aestivum* L.). *Genetic Resources and Crop Evolution* 50 (7): 669–679. <https://doi.org/10.1023/a:1025077005401>
- Franaszek S, Salmanowicz B. 2021. Composition of low-molecular-weight glutenin subunits in common wheat (*Triticum aestivum* L.) and their effects on the rheological properties of dough. *Open Life Sciences* 16 (1): 641–652. <https://doi.org/10.1515/biol-2021-0059>
- Guzmán C, Crossa J, Mondal S, Govindan V, Huerta J, Crespo-Herrera L, Vargas M, Singh R, Ibba MI. 2022. Effects of glutenins (*Glu-1* and *Glu-3*) allelic variation on dough properties and bread-making quality of CIMMYT bread wheat breeding lines. *Field Crops Research* 284: 108585. <https://doi.org/10.1016/j.fcr.2022.108585>
- Hernández-Espinosa N, Posadas-Romano G, Cervantes-López F, González-Santoyo H, Santacruz-Varela A, Benítez-Riquelme I, Peña-Bautista RJ. 2013. Contribución de combinaciones de gluteninas a las características del gluten en poblaciones recombinantes de trigo. *Revista Fitotecnia Mexicana* 36 (1): 45–51.
- Ibba MI, Kiszonas AM, Morris CF. 2017. Influence of low-molecular-weight glutenin subunit haplotypes on dough rheology in elite common wheat varieties. *Cereal Chemistry* 94 (6): 1016–1027. <https://doi.org/10.1094/cchem-07-17-0137-r>
- Jackson EA, Morel MH, Sontag-Strohm T, Branlard G, Metakovsky EV, Redaelli R. 1996. Proposal for combining the classification systems of alleles of *Gli-1* and *Glu-3* loci in bread wheat (*Triticum aestivum* L.). *Journal of Genetics and Breeding* 50: 321–336.
- Kiszonas AM, Morris CF. 2018. Wheat breeding for quality: A historical review. *Cereal Chemistry* 95 (1): 17–34. <https://doi.org/10.1094/cchem-05-17-0103-fi>
- Ma F, Kim J, Baik BK. 2020. Influences of high-molecular-weight glutenin subunits and rye translocations on dough-mixing properties and sugar-snap cookie-baking quality of soft winter wheat. *The Journal of the Science of Food and Agriculture* 100 (10): 3850–3856. <https://doi.org/10.1002/jsfa.10423>
- Ma F, Kim J, Cho E, Brown-Guedira G, Park CS, Baik BK. 2019. HMW-GS composition and rye translocations of U.S. eastern soft winter wheat and their associations with protein strength. *Journal of Cereal Science* 89: 102799. <https://doi.org/10.1016/j.jcs.2019.102799>
- Martínez-Cruz E, Espitia-Rangel E, Villaseñor-Mir HE, Hortelano-Santa Rosa R, Rodríguez-García MF, Peña-Bautista RJ. 2014. La calidad industrial de la masa y su relación con diferentes loci de gluteninas en trigo harinero (*Triticum aestivum* L.). *Agrociencia* 48 (4): 403–411.

- Moiraghi M, Vanzetti L, Pflüger L, Helguera M, Pérez GT. 2013. Effect of high molecular weight glutenins and rye translocations on soft wheat flour cookie quality. *Journal of Cereal Science* 58 (3): 424–430. <https://doi.org/10.1016/j.jcs.2013.08.007>
- Muñoz-Calixto JJ, Guzmán-García C, Pinzón-Martínez DL, Gutiérrez-Ibáñez AT, Rajaram, S, Solís-Méndez AD, Mariezcurrena-Berasain MD. 2022. Identificación de alelos de gluteninas y gliadinas en harinas de trigo entero (*Triticum aestivum* L.) y su relación con la calidad panadera. *Revista de la Facultad de Agronomía* 121 (2): 118. <https://doi.org/10.24215/16699513e118>
- Payne PI, Lawrence GJ. 1983. Catalogue of alleles for the complex gene loci, *Glu-A1*, *Glu-B1*, and *Glu-D1* which code for high-molecular-weight subunits of glutenin in hexaploid wheat. *Cereal Research Communications* 11 (1): 29–35.
- Sarkar S, Singh AM, Ahlawat AK, Chakraborti M, Singh SK. 2015. Genetic diversity of bread wheat genotypes based on high molecular weight glutenin subunit profiling and its relation to bread making quality. *Journal of Plant Biochemistry and Biotechnology* 24 (2): 218–224. <https://doi.org/10.1007/s13562-014-0261-y>
- Sharma S, Katyal M, Singh N, Singh AM, Ahlawat AK. 2021. Comparison of effect of using hard and soft wheat on the high molecular weight-glutenin subunits profile and the quality of produced cookie. *Journal of Food Science and Technology* 59 (7): 2545–2561. <https://doi.org/10.1007/s13197-021-05272-5>
- Singh NK, Shepherd KW, Cornish GB. 1991. A simplified SDS-PAGE procedure for separating LMW subunits of glutenin. *Journal of Cereal Science* 14 (3): 203–208. [https://doi.org/10.1016/S0733-5210\(09\)80039-8](https://doi.org/10.1016/S0733-5210(09)80039-8)
- Singh NK, Shepherd KW. 1988. Linkage mapping of genes controlling endosperm storage proteins in wheat. *Theoretical and Applied Genetics* 75 (4): 628–641. <https://doi.org/10.1007/BF00289132>
- Wang Y, Zhen S, Luo N, Han C, Lu X, Li X, Xia X, He Z, Yan Y. 2016. Low molecular weight glutenin subunit gene *Glu-B3h* confers superior dough strength and breadmaking quality in wheat (*Triticum aestivum* L.). *Scientific Reports* 6 (1): 1–12. <https://doi.org/10.1038/srep27182>
- Zhang M, Jia R, Ma M, Yang T, Sun Q, Li M. 2023. Versatile wheat gluten: Functional properties and application in the food-related industry. *Critical reviews in food science and nutrition* 63 (30): 10444–10460. <https://doi.org/10.1080/10408398.2022.2078785>
- Zhang P, Yao J, Ma H, Song G. 2020. Physicochemical and rheological properties of the derivatives of Ningmai 9 wheat and their relationship with sugar snap cookie diameter. *Australian Journal of Crop Science* 14 (7): 1150–1156. <https://doi.org/10.21475/ajcs.20.14.07.p2451>
- Zhang X, Jin H, Zhang Y, Liu D, Li G, Xia X, Zhonghu H, Zhang A. 2012. Composition and functional analysis of low-molecular-weight glutenin alleles with Aroona near-isogenic lines of bread wheat. *BMC Plant Biology* 12 (1): 243. <https://doi.org/10.1186/1471-2229-12-243>
- Zhang X, Zhang BQ, Wu HY, Lu CB, Lü GF, Liu DT, Man LI, Jiang W, Song GH, Gao DR. 2018. Effect of high-molecular-weight glutenin subunit deletion on soft wheat quality properties and sugar-snap cookie quality estimated through near-isogenic lines. *Journal of Integrative Agriculture* 17 (5): 1066–1073. [https://doi.org/10.1016/S2095-3119\(17\)61729-5](https://doi.org/10.1016/S2095-3119(17)61729-5)

## VEGETATIVE GROWTH OF PEACH TREES [*Prunus persica* (L.) Batsch] ASSOCIATED WITH NATIVE SQUASH (*Cucurbita pepo* ssp. *pepo* L.) AND BAYOCOTE (*Phaseolus coccineus* L.) IN MILPA INTERCROPPED WITH FRUIT TREES (MIAF) SYSTEMS

Eduardo Muñoz-Ruiz<sup>1</sup>, Horacio Santiago-Mejía<sup>1\*</sup>, Ildefonso Ronquillo-Cedillo<sup>1</sup>,  
Rocio Albino-Garduño<sup>1</sup>, José Isabel Cortés-Flores<sup>2</sup>, Julie Grossman<sup>3</sup>

<sup>1</sup>Universidad Intercultural del Estado de México. Maestría en Gestión de la Innovación Rural Sustentable. Libramiento Francisco Villa S/N, Colonia Centro, San Felipe del Progreso, State of Mexico, Mexico. C. P. 50640.

<sup>2</sup>Colegio de Postgraduados Campus Montecillo. Posgrado en Edafología. Carretera México- Texcoco km 36.5, Montecillo, Texcoco, State of Mexico, Mexico. C. P. 56264.

<sup>3</sup>University of Minnesota. Department of Horticultural Science. 1970 Folwell Ave., Saint Paul, MN, USA. C. P. 55108.

\* Author for correspondence: horacio.santiago@uiem.edu.mx

**Citation:** Muñoz-Ruiz E, Santiago-Mejía H, Ronquillo-Cedillo I, Albino-Garduño R, Cortés-Flores JI, Grossman J. 2024. Vegetative growth of peach trees [*Prunus persica* (L.) Batsch] associated with native squash (*Cucurbita pepo* ssp. *pepo* L.) and bayocote (*Phaseolus coccineus* L.) in Milpa Intercropped with Fruit Trees system (MIAF) systems. *Agrociencia* 58(5): 543-556. <https://doi.org/10.47163/agrociencia.v58i5.3071>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: September 25, 2023.

Approved: June 03, 2024.

**Published in Agrociencia:**  
August 05, 2024.

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



### ABSTRACT

The scarcity of basic foodstuffs in the Mazahua region of the State of Mexico, Mexico, reflects the scarcity of arable land in peasant agriculture. This issue was exacerbated in the early years of the Milpa Intercropped with Fruit Trees system (MIAF, for its Spanish acronym), because the fruit tree strip occupied up to 40 % of the area while producing no food or income during its vegetative growth stage. Native squash (*Cucurbita pepo* L.) and bayocote (*Phaseolus coccineus* L.) are basic species in the Mazahua diet, but it is unknown whether they have an adverse effect on the vegetative growth of the newly planted peach trees [*Prunus persica* (L.) Batsch] when grown in association. The goal of this research was to evaluate the effect of native squash and bayocote, grown in the fruit tree strip of the MIAF system, on the vegetative growth of peach trees for efficient soil intensification during the juvenile period of the tree. The treatments primarily involved associating peach trees with native squash, bayocote, and uncovered soil. The experimental design comprised randomized blocks with three replications. Vegetative growth, shoot biomass, root distribution, and soil moisture content were evaluated 60, 120, and 180 days after planting. Data were subjected to analysis of variance and comparison of means with the Tukey test ( $p \leq 0.05$ ) using the SAS 9.4 program. The native squash decreased the diameter and stem biomass of the peach trees since there was greater root overlap between the two species and less soil moisture. In contrast, with the association of the fruit tree with bayocote, the root distribution of the peach tree was greater, with no decrease in the diameter, height, or biomass of its stem. Local species such as bayocote have the potential to be grown in the fruit tree strip of the MIAF system in their first year of establishment.

**Keywords:** root distribution, crop association, biomass.

## INTRODUCTION

In the Mazahua region of the northwestern State of Mexico, Mexico, traditional agriculture still predominates, practiced by farmers owning less than 5 ha of land (Albino-Garduño *et al.*, 2021), who produce basic grains in rainfed and hillside conditions (Vásquez-González *et al.*, 2018). In this type of agriculture, maize yields and net incomes are low, and food production is not sufficient for rural families (Martínez-Borrego and Vallejo-Román, 2019).

To address this critical situation, the Milpa Intercropped with Fruit Trees (MIAF) system has been proposed, which is a multi-objective technology for smallholder farmers. MIAF optimizes arable land and increases employment (Cortés *et al.*, 2012), pursues food security (Padilla-Fidencio *et al.*, 2022), controls water erosion, and increases net income (Ruiz-Mendoza *et al.*, 2012), precipitation infiltration (Camas-Gómez *et al.*, 2012), and atmospheric carbon sequestration (Arriaga-Vázquez *et al.*, 2020).

The MIAF system alternates strips of milpa with strips of fruit trees with high-quality varieties for the fresh fruit market (Cortés *et al.*, 2012). On slopes with gradients greater than 20 %, fruit tree strips occupy 40 % of the area; however, they do not provide income during the first years of their establishment because of the formation of the support system and vegetative growth. The limited availability of land makes it necessary to establish annual species in the strip for food production without detriment to the vegetative growth of the fruit trees.

The literature reports a wide range of responses when associating fruit trees with annual species, depending on soil and climatic conditions as well as the species itself. On one hand, competition between ground cover species and newly planted peach trees decreases their growth and eventual productivity (Welker and Glenn, 1991). Competition for moisture and nutrients between the roots of newly planted peach trees and clover-grass mixtures reduces root biomass and total tree biomass (Forey *et al.*, 2017). With grass, their size, yield (Tworkoski and Glenn, 2010), root depth, root distribution area, and stem diameter are reduced (Parker and Meyer, 1996).

However, other research shows that there is complementarity between peach trees and annual plants. Peach trees (*Prunus persica* (L.) Batsch) associated with native weeds have higher growth due to higher nitrogen availability, higher organic matter and microbial biomass, better nutrient recycling, and lower nutrient loss through leaching and runoff (Zhang *et al.*, 2018). With clover, initially, stem diameter decreased, but by the third year, stems were larger than peach trees grown without cover due to greater access to water and nutrients despite root competition (Reeve *et al.*, 2017). In addition, the association of peach trees with clover improves pest control because of the increase of generalist predatory arthropods (Wan *et al.*, 2014). Similarly, the association of grass with olive trees increases the colonization of arbuscular mycorrhizal fungi (Palla *et al.*, 2020).

Local annual species have been studied within the milpa. Native squash (*Cucurbita pepo* ssp. *Pepo* L.) is used for its flowers, vegetable squash, mature squash, and seeds.

From bayocote (*Phaseolus coccineus* L.), the grain is used. These species are consumed and marketed throughout the northern region of the State of Mexico (Vásquez-González *et al.*, 2018), which allows for a more sustainable agroecosystem (Acevedo *et al.*, 2020). This study set out to evaluate the effects of native squash and bayocote, grown in the fruit tree strip of the MIAF system, on the vegetative growth of peach trees for efficient land intensification during the juvenile cycle of the fruit tree. This was motivated by the scarcity of arable land and research on the association of peach trees, native squash, and bayocote in the MIAF system.

## MATERIALS AND METHODS

In the spring-summer cycle of 2020, from May 25 to November 22, an experimental plot of the MIAF system was established with Mr. Manuel Téllez Hernández from the community of San Pablo Tlalchichilpa, municipality of San Felipe del Progreso, located in the Mazahua region in the northwest of the State of Mexico, Mexico (19° 42' 58.98" N, 99° 59' 6.19" W), at an altitude of 2669 m. The soil of the experimental plot is Andosol, with a temperate sub-humid climate (Cw) and rainfall of 800 to 1100 mm during the crop period (INEGI, 2009).

The result of the soil analysis, which was carried out at the Soil Genesis Laboratory of the Postgraduate College, Mexico, showed a pH of 4.42 and an organic matter content of 2.29 % at a depth of 0 to 30 cm. The bulk density of the soil is clayey, with a sandy clay loam texture, dark brown when wet and brown when dry.

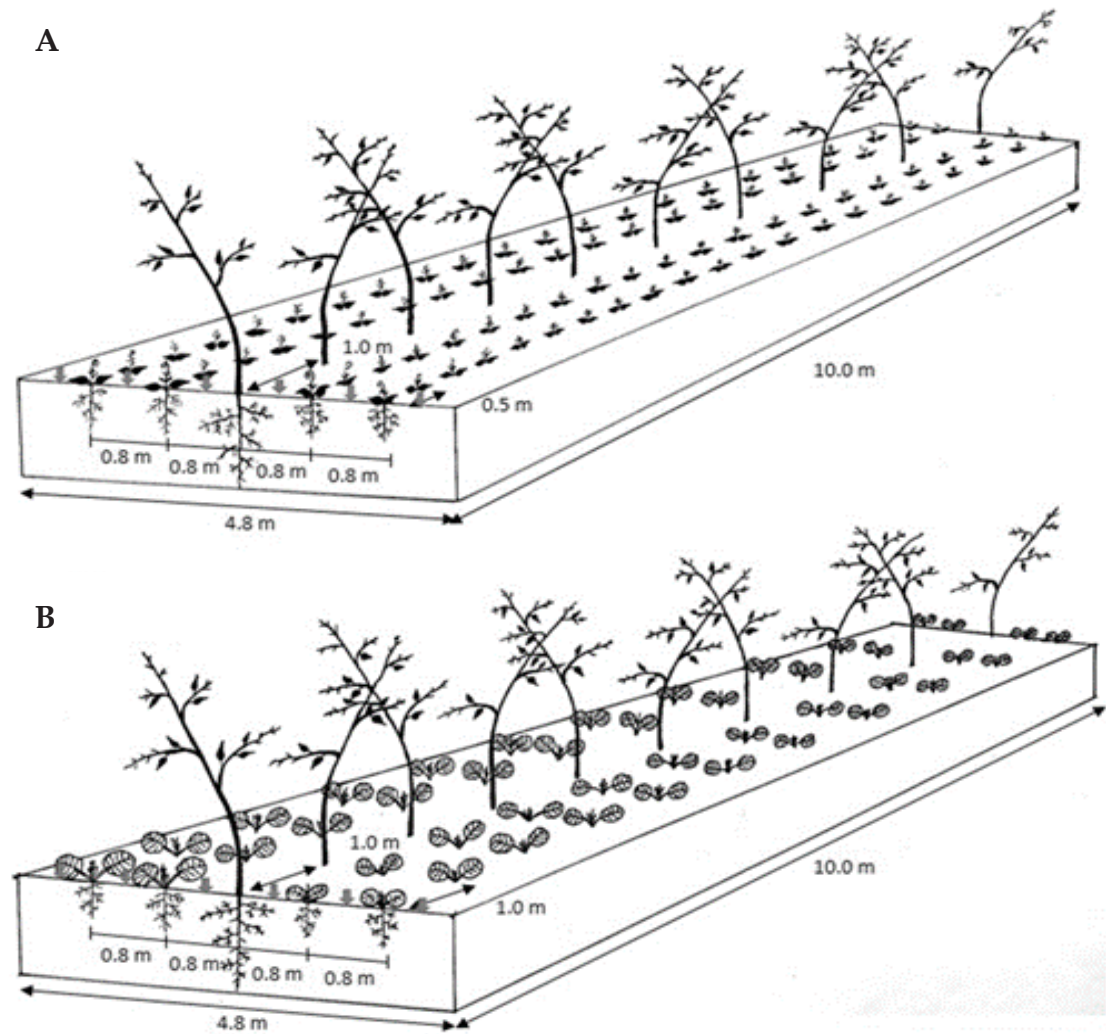
### Treatments and experimental design

The treatments evaluated with local species were: peach tree (*Prunus persica* (L.) Batsch) associated with native squash (*Cucurbita pepo* ssp. *pepo* L.), peach tree associated with bayocote (*Phaseolus coccineus* L.), and peach tree in soil without cover as a control. The experimental design consisted of randomized blocks with three replications. The experimental unit was delimited by a strip 4.8 m wide and 10 m long. Each strip of the peach tree is a replica. In the center of the strip, peach trees of the cultivar 'Azteca de Oro' were planted 1 m apart, for a total of 10 peach trees per treatment.

### Crop management

The experimental plot was established on March 16, 2020, on a slope with a gradient of less than 20 %. The MIAF system modules had a width of 14.4 m, formed by the fruit tree strip of 4.8 m and two flanking strips of milpa of the same size. In the fruit tree strip, the planting of the native squash, bayocote, and peach trees took place on May 26, 2020. The planting of the two annual species was established two furrows (0.8 m each) away from the peach tree row on both contiguous sides (Figure 1).

The distance from the furrows to the peach tree trunks was 0.8 and 1.6 m. The distances between bushes of native squash and bayocote were 1 and 0.5 m, respectively; the number of plants per bush was one and two, respectively. The native squash



**Figure 1.** Experimental unit design of the fruit tree strip of the Milpa Intercropped with Fruit Trees (MIAF) system. A: Peach trees (*Prunus persica* (L.) Batsch) intercropped with bayocote (*Phaseolus coccineus* L.); B: peach trees intercropped with native squash (*Cucurbita pepo* ssp. *pepo* L.).

and bayocote were fertilized with 120-140-40 kg ha<sup>-1</sup> of N-P-K and 10 Mg ha<sup>-1</sup> of precomposted manure. Stocking density was 0.83 and 3.33 plants m<sup>-2</sup>, respectively. At planting, all P, K, manure, and one-third of the N were applied; the remainder was placed 86 days after planting. Peach tree fertilization was done with the 20-20-20 g dose of N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O<sub>5</sub> in combination with 1 kg of precomposted sheep manure per peach tree. The local species and peach trees were maintained with auxiliary irrigation for the first 60 days after establishment. Weed control was manual and permanent.

### Variables evaluated

The variables studied were measured at 60, 120, and 180 days after sowing (DAS) in the case of native squash and bayocote, and days after planting (DAP) in the case of peach trees. The useful area sampled was 8 m long and 4.8 m wide, as the ends of each experimental unit were not evaluated.

### Vegetative growth of peach tree

To measure the vegetative growth of the peach shoot, six peach trees per treatment were measured in all replications. Height was measured from the branch insertion to the trunk to the apex of the main branch using a tape measure. Diameter was measured with a digital vernier (electronic digital caliper, 0–300 mm) 2 cm above the graft. With the data obtained, the cumulative growth rate was calculated, in millimeters for diameter and centimeters for height, at 60, 120, and 180 days, using the following equation (Poorter and Lewis, 1986):

$$TA = \frac{(\ln W_2 - \ln W_1)}{(t_2 - t_1)}$$

where  $TA$  is the cumulative growth rate;  $W_1$  and  $W_2$  are diameter 1 and 2; and  $t_1$  and  $t_2$  are times 1 and 2.

### Peach tree stem biomass

On each sampling date, one tree was cut at ground level for each replicate and dehydrated in a drying oven (Lumiteell MR HTP-42, Mexico) at 72 °C to a constant weight (Díaz-Ríos *et al.*, 2016). Subsequently, it was weighed on a digital balance (Torrey L-EQ 5/10, Mexico) and recorded in  $\text{g plant}^{-1}$ .

### Root distribution

The destructive profile wall method (Atkinson and Wilson, 1980) was used, in which a trench was dug in the soil perpendicular to the peach tree strip in the MIAF system at the point of soil insertion with the peach tree stems, native squash, and bayocote. The dimensions of the trench were: 4.8 m long, corresponding to the width of the strip of fruit trees in the MIAF system, and 0.9 m wide; the depth of the trench varied according to the depth of the roots at the time of sampling.

Root exposure and measurement were done according to Albino-Garduño *et al.* (2015). The root distribution of peach trees, native squash, and bayocote was recorded on a millimeter sheet, indicating in each quadrant the presence or absence of roots. Color-based root differentiation was used, with the peach tree's roots being dark brown and the native squash and bayocote being light brown. Root distribution was calculated using the total area occupied by the root in the trench profile and the overlapping areas of each species. Results were plotted in Excel and reported in  $\text{cm}^2$ .

### Soil moisture content

Soil was sampled between the native squash rows and bayocote at 0.4, 1.2, and 2 m on both contiguous sides of the peach tree row, at depths of 0–20, 20–40, 40–60, and 60–80 cm, for a total of 24 subsamples per experimental unit. Soil samples were obtained with a T-type auger (Oakfield, USA). The time of sampling was standardized within each treatment, from 8:00 to 14:00 h. The samples were placed in aluminum cans and weighed in the field with a digital scale (Torrey L-EQ 5/10, Mexico). They were then placed in a drying oven (Lumiteell HTP-42, Mexico) at 105 °C until they reached constant weight. Soil moisture content (% w/w) was calculated with the following formula (Xylogiannis *et al.*, 2020):

$$\frac{\text{Wet weight} - \text{Constant dry weight}}{\text{Constant dry weight}} * 100$$

### Statistical analysis

The data were tested for normality of errors (Shapiro-Wilks) and homogeneity of variances (Bartlett) prior to performing other analyses. The variables vegetative growth and peach shoot biomass were analyzed as a one-factorial design (three treatments: peach tree and native squash, bayocote, or soil without cover as a control). Soil moisture content was analyzed in a 3 x 6 x 4 factorial design (the three treatments evaluated, six depths, and four furrows of the experimental unit).

The data of the measured variables were analyzed through an analysis of variance and comparison of means with the Tukey test ( $p \leq 0.05$ ) with the SAS 9.4 program. In the case of root distribution, data were analyzed descriptively; quadrants with root presence were summed to calculate the area and its overlap (peach tree, native squash, and bayocote) and plotted to scale using the Excel program (Albino-Garduño *et al.*, 2015).

## RESULTS AND DISCUSSION

### Vegetative growth of peach tree

Native squash (*Cucurbita pepo* ssp. *pepo*. L.) and bayocote (*Phaseolus coccineus* L.) had no effect on tree height compared to the treatment without soil cover ( $p = 0.0487$ ) on the three sampling dates (60, 120, and 180 DAP) (Table 1); however, stem diameter was affected. From 120 DAP onwards, peach trees associated with native squash had a smaller diameter than those grown in uncovered soil.

Peach tree shoot biomass at 60 and 120 DAP was similar in all treatments, but at 180 DAP it was lower in peach trees associated with native squash (Table 2).

The diameter, height, and biomass of peach tree stems associated with bayocote were unaffected, unlike those of soil without vegetative cover. However, there was a positive

**Table 1.** Cumulative rate of growth in height and diameter of peach trees (*Prunus persica* (L.) Batsch) in the strip of the Milpa Intercropped with Fruit Trees (MIAF) system associated with native squash (*Cucurbita pepo* ssp. *pepo* L.) and bayocote (*Phaseolus coccineus* L.).

Treatment	Days after planting					
	60		120		180	
	Height (cm)	Diameter (mm)	Height (cm)	Diameter (mm)	Height (cm)	Diameter (mm)
Native squash	8.17 a	1.67 a	23.39 a	3.71 a	30.66 a	5.05 a
Bayocote	9.00 a	2.66 a	18.16 a	5.86 ab	24.10 a	6.99 ab
Uncovered soil	10.15 a	3.43 a	23.62 a	7.55 b	32.38 a	9.87 b

Means with a common letter are not significantly different ( $p > 0.05$ ).

**Table 2.** Stem biomass of peach trees (*Prunus persica* (L.) Batsch) associated with native squash (*Cucurbita pepo* ssp. *pepo* L.) and bayocote (*Phaseolus coccineus* L.) in the fruit tree strip of the Milpa Intercropped with Fruit Trees (MIAF) system.

Treatment	Days after planting		
	60 (g plant <sup>-1</sup> )	120 (g plant <sup>-1</sup> )	180 (g plant <sup>-1</sup> )
Native squash	6.50 a	11.91 a	13.83 a
Bayocote	3.29 a	11.78 a	81.28 b
Uncovered squash	4.28 a	21.78 a	69.61 b

Means with a common letter are not significantly different ( $p > 0.05$ ).

effect on root distribution, since at the end of the sampling period (180 DAP), the roots of peach trees associated with bayocote had a greater distribution of 36.4 and 37.5 % in comparison to the soil without mulch and with native squash, respectively (Table 3). The root distribution area of peach trees was similar when grown with native squash as in soil without cover.

The effect on stem diameter, biomass, and root distribution of peach trees associated with native squash or bayocote is related to the area of overlap between peach tree roots and annual species. In all sampling dates, the root overlap area was greater in peach trees associated with native squash than with bayocote (Figures 2 and 3). At 180 DAP, the highest value was found; peach tree roots had an overlap of 74.57 % of their total area with native squash roots, compared to 28.96 % with bayocote roots (Figures 2 and 3). This greater overlap was because native squash has a greater root distribution than bayocote (Table 4). In addition, less competition between peach tree and bayocote roots favored the growth of peach tree roots.

**Table 3.** Root distribution and root overlap area of peach trees (*Prunus persica* (L.) Batsch) associated with native squash (*Cucurbita pepo* ssp. *pepo* L.) and bayocote (*Phaseolus coccineus* L.) in the fruit tree strip of the Milpa Intercropped with Fruit Trees (MIAF) system.

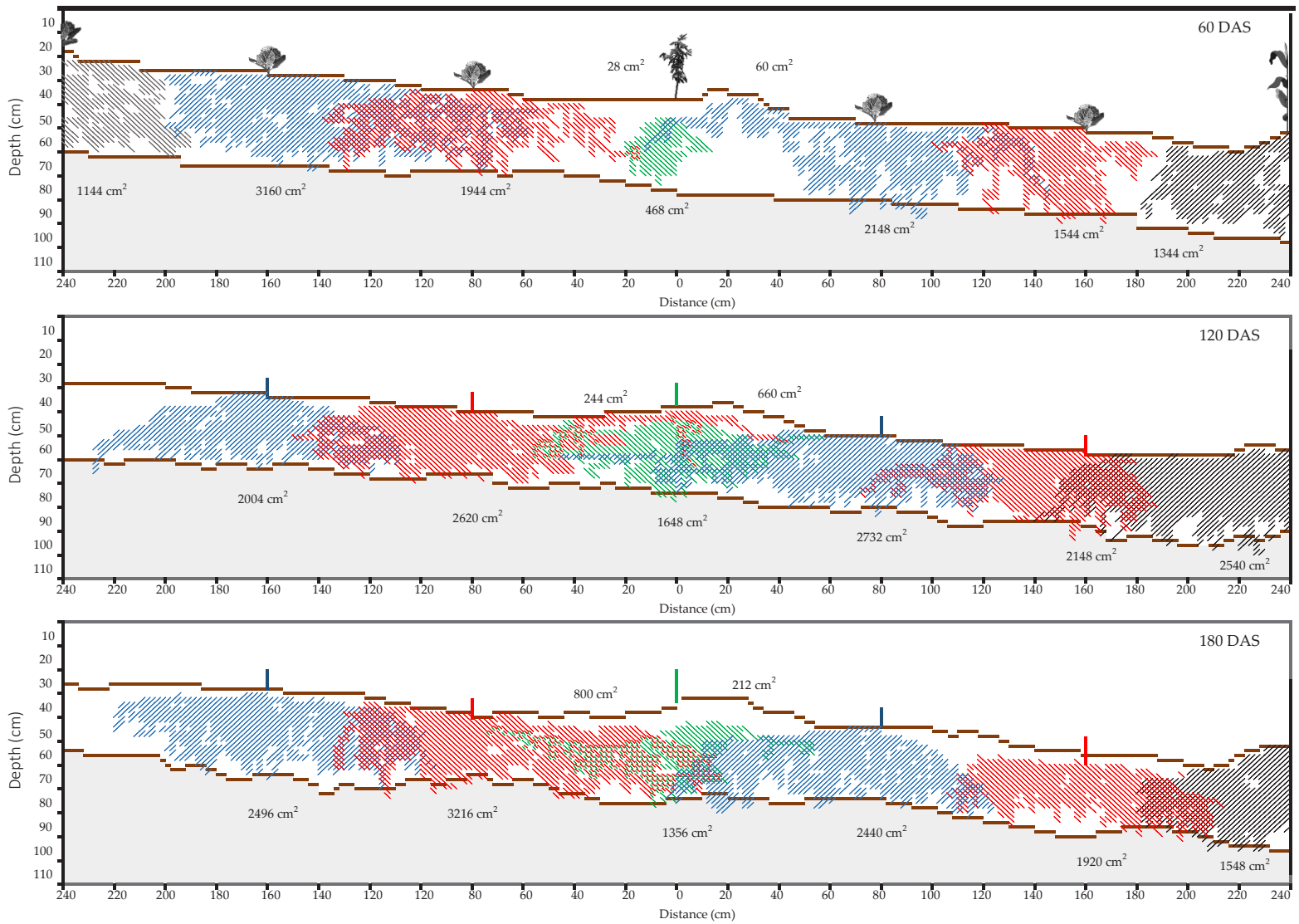
Treatment	Days after planting					
	60		120		180	
	Root distribution (cm <sup>2</sup> )	Overlap (cm <sup>2</sup> )	Root distribution (cm <sup>2</sup> )	Overlap (cm <sup>2</sup> )	Root distribution (cm <sup>2</sup> )	Overlap (cm <sup>2</sup> )
Native squash	468	88	1648	904	1356	1012
Bayocote	800	4	892	528	2168	628
Uncovered	412	-*	1192	-*	1380	-*

\*Uncovered soil. The overlap area of the root distribution corresponds to the total sum of the sampled rows 2 and 3 (contiguous to the peach trees).

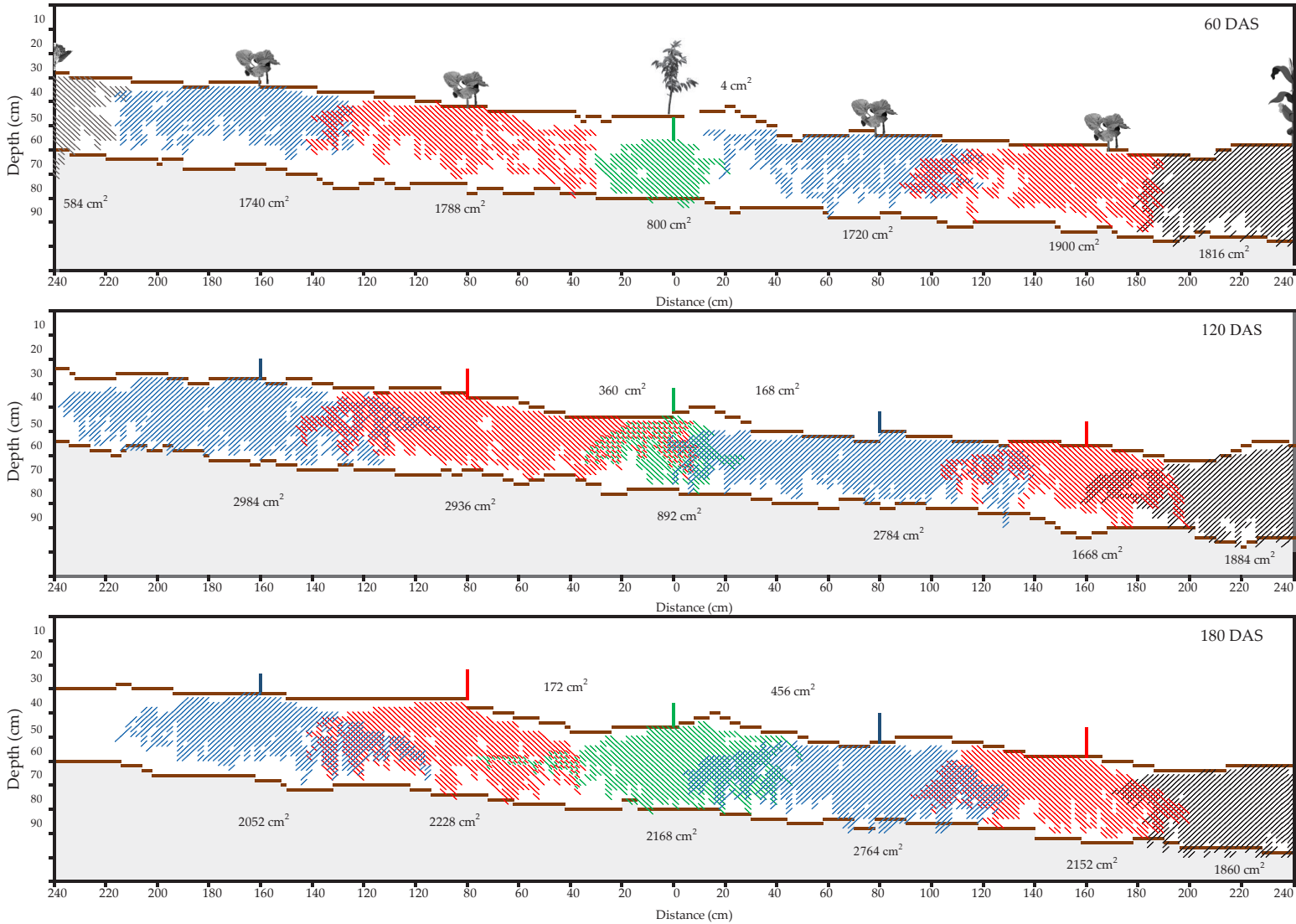
Soil moisture content was related to the areas of overlap between peach and native squash and bayocote roots. At 120 DAP ( $p < 0.0001$ ), less overlap or competition between peach and bayocote roots maintained higher soil moisture content in the fruit tree strip compared to that grown with peach tree and native squash or no cover crop (Table 5). At 180 DAP ( $p < 0.0001$ ), when it had stopped raining, moisture content was similar in the strip cultivated with peach trees and bayocote or native squash; however, moisture use was more efficient when there was greater peach tree root distribution and less overlap area in association with bayocote, without reducing stem diameter growth or peach tree biomass production.

During the rainfall period, at 60 and 180 DAS, native squash had a larger root distribution area than bayocote. A larger overlap area with peach tree roots resulted in lower peach stem biomass. This root competition increased moisture levels in the fruit tree strip planted with native squash rather than bayocote. Young peach trees are very sensitive to moisture competition when associated with grass and legume mixtures (Forey *et al.*, 2017), limiting deep root (Gómez and Gómez, 2011) and aerial growth (Welker and Glenn, 1991). Competition for soil moisture affects stem elongation (Sharma *et al.*, 2018) and interferes with peach tree root architecture and penetration (Colombi *et al.*, 2018).

In contrast, the smaller distribution and overlapping area of bayocote roots with those of peach trees and the greater availability of soil moisture (120 DAP) favored a larger distribution area of its roots at 180 DAS, even though the values for uncovered soil were similar to native squash. The compact root morphology of legumes (Reeve *et al.*, 2017) and some native species (Zhang *et al.*, 2018) makes them less competitive for moisture and nutrients. Mulinge *et al.* (2017) mention that the legumes dolichos (*Lablab purpureus*), mucuna (*Mucuna pruriens*), and cowpea (*Vigna unguiculata*), used as cover crops, do not compete for soil moisture and improve root distribution of orange fruit



**Figure 2.** Root distribution area of peach trees (*Prunus persica* (L.) Batsch) (green) associated with native squash (*Cucurbita pepo* ssp. *pepo* L.) (blue and red) in two contiguous rows at 60, 120, and 180 days after sowing (DAS). The numbers on top of the peach tree represent the area where the tree roots overlap with those of native squash. The numbers at the bottom of each root correspond to the root distribution area of each plant.



**Figure 3.** Root distribution area of peach trees (*Prunus persica* (L.) Batsch) (green) associated with bayocote (*Phaseolus coccineus* L.) (blue and red) in two contiguous rows at 60, 120, and 180 days after sowing (DAS). The numbers on top of the peach tree represent the area where the tree roots overlap with those of bayacote. The numbers at the bottom of each root correspond to the root distribution area of each plant.

**Table 4.** Root distribution area of native squash (*Cucurbita pepo* ssp. *pepo* L.) and bayocote (*Phaseolus coccineus* L.) associated with peach trees (*Prunus persica* (L.) Batsch) in the fruit tree strip of the Milpa Intercropped with Fruit Trees (MIAF) system, corresponding to the average of the four sampled rows.

Treatment	Days after sowing		
	60 (cm <sup>2</sup> )	120 (cm <sup>2</sup> )	180 (cm <sup>2</sup> )
Native squash	2199	2376	2518
Bayocote	1787	2593	2299

**Table 5.** Soil moisture content (% w/w) in the strip cultivated with peach trees (*Prunus persica* (L.) Batsch) associated with native squash (*Cucurbita pepo* ssp. *pepo* L.) or bayocote (*Phaseolus coccineus* L.).

Treatment	Days after sowing		
	60	120	180
Native squash	20.86 b	25.06 b	16.72 a
Bayocote	19.81 a	25.47 c	16.64 a
Uncovered soil	19.78 a	23.88 a	17.82 b

Means with a common letter are not significantly different ( $p > 0.05$ ).

trees. Vegetative growth of fruit trees is positively correlated to soil moisture and root development (Abrisqueta *et al.*, 2017). Likewise, van Noordwijk *et al.* (2015) mention that the roots of fruit trees and annual crops are distributed differently in their early stages of development to avoid competition for moisture.

At the end of the rainy season (180 DAS), moisture was higher in the uncovered fruit tree strip than in the strips cultivated with native squash or bayocote, but this no longer modified the vegetative growth of the peach trees. The stem diameter of peach trees grown with native squash was smaller than with uncovered soil. González *et al.* (2012) found a similar response in peach trees grown without weed control in the strip, as it restricted the surface growth of tree roots.

## CONCLUSIONS

In the first year of establishment of the experimental plot, using the Milpa Intercropped with Fruit Trees system (MIAF) with peach tree (*Prunus persica* (L.) Batsch) strips associated with native squash (*Cucurbita pepo* ssp. *pepo* L.) and bayocote (*Phaseolus*

*coccineus* L.), vegetative growth (height and diameter) and biomass of peach trees with bayocote were the same as in the uncovered fruit tree strip. This suggests that bayocote does not inhibit the vegetative growth of peach trees. In addition, bayocote increased the root distribution area of the peach tree compared to the association with native squash or uncovered soil. The greater root distribution of the peach tree favored the utilization of the limited moisture at 180 days after sowing, without detracting from its growth and biomass production. The native squash restricted vegetative growth of peach trees, reflected in a lower stem diameter and biomass compared to peach trees grown without cover, due to greater root competition and lower moisture availability.

#### ACKNOWLEDGEMENTS

Our thanks to the Consejo Mexiquense de Ciencia y Tecnología (COMECYT) for the financial grant from the Programa de Desarrollo Social Becas Comecyt-Edomex Beca de Posgrado Edomex Primera Promoción 2021, with folio: 2021BPC1-M0563.

#### REFERENCES

- Abrisqueta I, Conejero W, López-Martínez L, Vera JM, Ruiz-Sánchez MC. 2017. Root and aerial growth in early-maturing peach trees under two crop load treatments. *Spanish Journal of Agricultural Research* 15 (2): e0803. <https://doi.org/10.5424/sjar/2017152-10714>
- Acevedo M, Pixley K, Zinyengere N, Meng S, Tufan H, Cichy K, Bizikova L, Isaacs K, Ghezzi-Kopel K, Porciello J. 2020. A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nature Plants* 6 (10): 1231–1241. <https://doi.org/10.1038/s41477-020-00783-z>
- Albino-Garduño R, Santiago-Mejía H, Avendaño-Gómez A, González-Álvarez L, Cruz-Reyes R. 2021. Peasant knowledge about maize fertilization in Mazahua (Jñatjo) communities of Mexico. *Agricultura, Sociedad y Desarrollo* 18 (2): 305–320. <https://doi.org/10.22231/asyd.v18i2.1002>
- Albino-Garduño R, Turrent-Fernández A, Cortés-Flores JI, Livera-Muñoz M, Mendoza-Castillo MC. 2015. Distribución de raíces y de radiación solar en el dosel de maíz y frijol intercalados. *Agrociencia* 49 (5): 513–531.
- Arriaga-Vázquez AM, Martínez-Menez MR, Rubiños-Panta JE, Fernández-Reynoso DS, Delgadillo-Martínez J, Vázquez-Alarcón A. 2020. Propiedades químicas y biológicas de los suelos en milpa intercalada con árboles frutales. *Terra Latinoamericana* 38 (3): 465–474. <https://doi.org/10.28940/terra.v38i3.599>
- Atkinson D, Wilson SA. 1980. The growth and distribution of fruit tree roots: some consequences for nutrient uptake. *Acta Horticulturae* 92: 137–150. <https://doi.org/10.17660/actahortic.1980.92.17>
- Camas-Gómez R, Turrent-Fernández A, Cortés-Flores JI, Livera-Muñoz M, González-Estrada A, Villar-Sánchez B, López-Martínez J, Espinoza-Paz N, Cadena-Iñiguez P. 2012. Erosión del suelo, escurrimiento y pérdida de nitrógeno y fósforo en laderas bajo diferentes sistemas de manejo en Chiapas, México. *Revista Mexicana de Ciencias Agrícolas* 3 (2): 231–243.

- Colombi T, Chagas-Torres L, Walter A, Keller T. 2018. Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth – A vicious circle. *Science of The Total Environment* 626: 1026–1035. <https://doi.org/10.1016/j.scitotenv.2018.01.129>
- Cortés FJI, Torres ZJP, Turrent FA, Hernández RE, Ramos SA, Jiménez SL. 2012. Manual actualizado para el establecimiento y manejo del sistema Milpa Intercalada con Árboles Frutales (MIAF) en laderas. Colegio de Postgraduados: Montecillo, México. 30 p.
- Díaz-Ríos MJ, Vázquez-Alarcón A, Uribe-Gómez M, Sánchez-Vélez A, Lara-Bueno A, Cruz-León A. 2016. Ecuaciones alométricas para estimar biomasa y carbono en aile obtenidas mediante un método no destructivo. *Revista Mexicana de Ciencias Agrícolas* 16: 3235–3249.
- Forey O, Temani F, Wery J, Jourdan C, Metay A. 2017. Effect of combined deficit irrigation and grass competition at plantation on peach tree root distribution. *European Journal of Agronomy* 91: 16–24. <https://doi.org/10.1016/j.eja.2017.08.008>
- Gómez-Sierra LA, Gómez-Cano FA. 2011. Efecto de cuatro manejos del suelo sobre la densidad de raíces absorbentes en durazno [*Prunus persica* (L.) Batsch] a 10 cm de profundidad. *Cultura Científica* (9): 8–16.
- González J, Fernández JR, Santanatoglia OJ, del Pardo C. 2012. Desarrollo radical en plantas de duraznero sometidas a diferentes manejos del suelo. *Revista de Investigaciones Agropecuarias* 38 (3): 276–281.
- INEGI (Instituto Nacional de Estadística y Geografía). 2009. México en cifras. San Pablo Tlalchichilpa, San Felipe del Progreso, México (150740103). Ciudad de México, México. <https://www.inegi.org.mx/app/areasgeograficas/?ag=15> (Retrieved: April 2021).
- Martínez-Borrego E, Vallejo-Román J. 2019. Pluriactividad, consumo y persistencia del maíz en dos municipios del noroeste del Estado de México. *Revista Euroamericana de Antropología* 7: 41–53. <https://doi.org/10.14201/rea201974153>
- Mulinge JM, Saha HM, Mounde LG, Wasilwa LA. 2017. Effect of legume cover crops on soil moisture and orange root distribution. *International Journal of Plant and Soil Science* 16 (4): 39–50. <https://doi.org/10.9734/ijpss/2017/32934>
- Padilla-Fidencio V, Albino-Garduño R, Santiago-Mejía H, Turrent-Fernández A, Ronquillo-Cedillo I, González-Pablo L. 2022. Intensification of milpa in the State of Mexico: Net incomes, food security and land equivalent ratio. *Agrociencia* 56 (4): 1–12. <https://doi.org/10.47163/agrociencia.v56i4.2453>
- Palla M, Turrini A, Cristani C, Caruso G, Avio L, Giovannetti M, Agnolucci M. 2020. Native mycorrhizal communities of olive tree roots as affected by protective green cover and soil tillage. *Applied Soil Ecology* 149: 103520. <https://doi.org/10.1016/j.apsoil.2020.103520>
- Parker ML, Meyer JR. 1996. Peach tree vegetative and root growth respond to orchard floor management. *HortScience* 31 (3): 330–333. <https://doi.org/10.21273/hortsci.31.3.330>
- Poorter H, Lewis C. 1986. Testing differences in relative growth rate: A method avoiding curve fitting and pairing. *Physiologia Plantarum* 67 (2): 223–226. <https://doi.org/10.1111/j.1399-3054.1986.tb02447.x>
- Reeve JR, Culumber CM, Black BL, Tebeau A, Ransom CV, Alston D, Rowley M, Lindstrom T. 2017. Establishing peach trees for organic production in Utah and the Intermountain West. *Scientia Horticulturae* 214: 242–251. <https://doi.org/10.1016/j.scienta.2016.11.040>
- Ruiz-Mendoza AD, Jiménez-Sánchez L, Figueroa-Rodríguez OL, Morales-Guerra M. 2012. Adopción del sistema milpa intercalada en árboles frutales por cinco municipios mixtes del Estado de Oaxaca. *Revista Mexicana de Ciencias Agrícolas* 3 (8): 1605–1621.

- Sharma MK, Singh A, Mushtaq R, Nazir N, Kumar A, Simnani SA, Khalil A, Bhat R. 2018. Effect of soil moisture on temperate fruit crops: A review. *Journal of Pharmacognosy and Phytochemistry* 7 (6): 2277–2282.
- Tworcoski TJ, Glenn DM. 2010. Long-term effects of managed grass competition and two pruning methods on growth and yield of peach trees. *Scientia Horticulturae* 126 (2): 130–137. <https://doi.org/10.1016/j.scienta.2010.06.020>
- van Noordwijk M, Lawson G, Hairiah K, Wilson J. 2015. Root distribution of trees and crops: Competition and/or complementarity. *In* *Tree-crop Interactions: Agroforestry in a Changing Climate*. CABI Digital Library: Wallingford, UK, pp: 221–257. <https://doi.org/10.1079/9781780645117.0221>
- Vásquez-González AY, Chávez-Mejía C, Herrera-Tapia F, Carreño-Meléndez F. 2018. Milpa y seguridad alimentaria: el caso de San Pedro El Alto, México. *Revista de Ciencias Sociales* 24 (2): 24–36. <https://doi.org/10.31876/rsc.v24i2.24817>
- Wan NF, Ji XY, Gu XJ, Jiang JX, Wu JH, Li B. 2014. Ecological engineering of ground cover vegetation promotes biocontrol services in peach orchards. *Ecological Engineering* 64: 62–65. <https://doi.org/10.1016/j.ecoleng.2013.12.033>
- Welker WV, Glenn DM. 1991. Growth response of young peach trees to distribution pattern of vegetation-free area. *HortScience* 26 (9): 1141–1142. <https://doi.org/10.21273/hortsci.26.9.1141>
- Xylogiannis E, Sofo A, Dichio B, Montanaro G, Mininni AN. 2020. Root-to-shoot signaling and leaf water use efficiency in peach trees under localized irrigation. *Agronomy* 10 (3): 437. <https://doi.org/10.3390/agronomy10030437>
- Zhang Y, Wang L, Yuan Y, Xu J, Tu C, Fisk C, Zhang W, Chen X, Ritchie D, Hu, S. 2018. Irrigation and weed control alter soil microbiology and nutrient availability in North Carolina Sandhill peach orchards. *Science of the Total Environment* 615: 517–525. <https://doi.org/10.1016/j.scitotenv.2017.09.265>

Agrociencia

## POST-HARVEST PRACTICES FOR THE PRODUCTION OF SPECIALTY COFFEES IN CHIAPAS, MEXICO

Etzli Itzel Morales-Reyes<sup>1</sup>, Martín Alejandro Bolaños-González<sup>1\*</sup>,  
Esteban Escamilla-Prado<sup>2</sup>, Antoine Libert-Amico<sup>3</sup>

<sup>1</sup>Colegio de Postgraduados Campus Montecillo. Posgrado en Hidrociencias. Carretera México-  
Texcoco km 36.5, Montecillo, Texcoco, State of Mexico, Mexico. C. P. 56264.

<sup>2</sup>Universidad Autónoma Chapingo. Centro Regional Universitario Oriente. Carretera Huatusco-  
Xalapa km 6, Huatusco, Veracruz, Mexico. C. P. 94100.

<sup>3</sup>Programa Mexicano del Carbono. Chiconautla 8-A, Lomas de Cristo, Texcoco, State of Mexico,  
Mexico. C. P. 56225.

\* Author for correspondence: bolanos@colpos.mx

### ABSTRACT

When it comes to specialty or high-quality coffees, sensory qualities are crucial because coffee marketers use samples to assess bean and cup quality, which is then used to create a score based on the Specialty Coffee Association (SCA) protocol. This score is then used to determine the purchase and price. This study provides a descriptive analysis of the processes developed during training for high-quality coffee production with three shade-grown organic coffee-producing organizations in the state of Chiapas. The goal was to improve harvest and post-harvest practices in order to increase the sensory quality of the coffee. Each training session used the washed, natural, and honey methods to process the coffee. Statistically significant differences were found in the different types of post-harvest processing for each organization. In the sensory analyses, washed coffees were classified as excellent (between 85 and 86 points). In general, the coffees obtained scored between 80 and 86 points, which, according to the SCA protocol, are classified as very good to excellent. The washed processes obtained the highest score; however, the natural and honey processes are a good alternative for producers who lack water during harvesting. Selective harvesting and monitoring of the fermentation processes help to increase the sensory quality of the coffee, improving its opportunity to access specialty markets in order to obtain better prices and greater stability in the medium term.

**Keywords:** organic coffee, cup quality, fermentation, specialty market, participatory workshops.

### INTRODUCTION

Mexico has a long tradition of coffee cultivation in sustainable agroforestry systems. In the states of Chiapas and Oaxaca, organic production is important; however, low prices, global market instability, and pests and diseases (Escamilla-Prado, 2016) have reduced economic sustainability, compromising socio-environmental sustainability. To overcome the challenges faced by producers, it is essential to seek alternatives to

**Citation:** Morales-Reyes EI,  
Bolaños-González MA, Escamilla-  
Prado E, Libert-Amico A. 2024.  
Post-harvest practices for the  
production of specialty coffees in  
Chiapas, Mexico.  
*Agrociencia* 58(5): 557-570.  
[https://doi.org/10.47163/  
agrociencia.v58i5.2880](https://doi.org/10.47163/agrociencia.v58i5.2880)

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: February 06, 2023.

Approved: April 23, 2024.

**Published in Agrociencia:**

July 04, 2024.

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



improve coffee quality, identify novel mechanisms for marketing, and bring producers closer to the final consumer.

In the last three decades, there has been an increase in the production of differentiated coffees (organic, fair trade, shade-grown) and specialty coffees (classified according to SCA criteria), in which the price is determined by the quality of the bean, sensory attributes, and management with sustainable practices and fair treatment, linking the producer with the final consumer through direct trade (Escamilla-Prado, 2012).

Coffee beans have a diverse and complex chemical composition, with over a thousand volatile and non-volatile compounds that contribute significantly to the beverage's distinct flavor (Magalhães *et al.*, 2021). Many factors influence their presence and concentration, from the plant to the cup. Poltronieri and Rossi (2016) point out that some of the transcendental factors to obtain quality are: 1) the optimal ripening stage; and 2) post-harvest processes. Puerta-Quintero (2000) assures that a good milling process has a favorable influence on obtaining quality grain; failures in this process can cause up to 80 % of quality problems (Aristizabal-Arias and Duque-Orrego, 2006). In this study, training on post-harvest practices was carried out with organizations of organic washed raw coffee producers in three municipalities in Chiapas, Mexico, interested in exploring the production of specialty coffees. The training was aimed at detecting opportunities for improvement in coffee processing. The principles of participatory rural appraisal were considered, where social collaboration is a fundamental ingredient to develop projects, promote a substantial improvement in the local quality of life, and conserve natural resources (Ramírez-García and Camacho-Bercherit, 2019). In this context, the objective was to improve harvest and post-harvest practices that help increase the sensory quality of coffee.

## MATERIALS AND METHODS

Training on post-harvest practices for the production of specialty coffee for the 2020–2021 harvest cycle was conducted. The first training was held from February 8 to 12, 2021, at the Comon Yaj Noptic Cooperative, in coordination with the technicians and the quality manager, at the Ranchería San Francisco facilities, municipality of La Concordia, Chiapas, Mexico (5° 46' 00" N, 92° 58' 56" W, at an altitude of 1700 m). The coffee samples used were collected at the same location where the training took place. Seventeen organic coffee producers participated, with the majority focusing on washed raw coffee for export.

The second training was carried out on February 22, 23, and 25, 2021, with Kulaktik Group, located in the municipality of Tenejapa, Chiapas, Mexico (16° 52' 28" N, 92° 28' 28" W, at an altitude of 1600 m). The coffee samples were collected in the same location where the training took place. Ten coffee producers participated, mainly focused on washed raw coffee for national sale.

The third training was held on March 16, 17, and 18, 2021, at the facilities of the Triunfo Verde Cooperative, located in Jaltenango de la Paz, a town in the municipality

of Angel Albino Corzo, Chiapas, Mexico (15° 52' 16" N, 92° 42' 37" W). The coffee samples were taken in a plot located at 15° 49' 41" N and 92° 44' 38" W, at an altitude of 1112 m, with the participation of 12 producers of organic coffee, mainly focused on washed raw coffee for export.

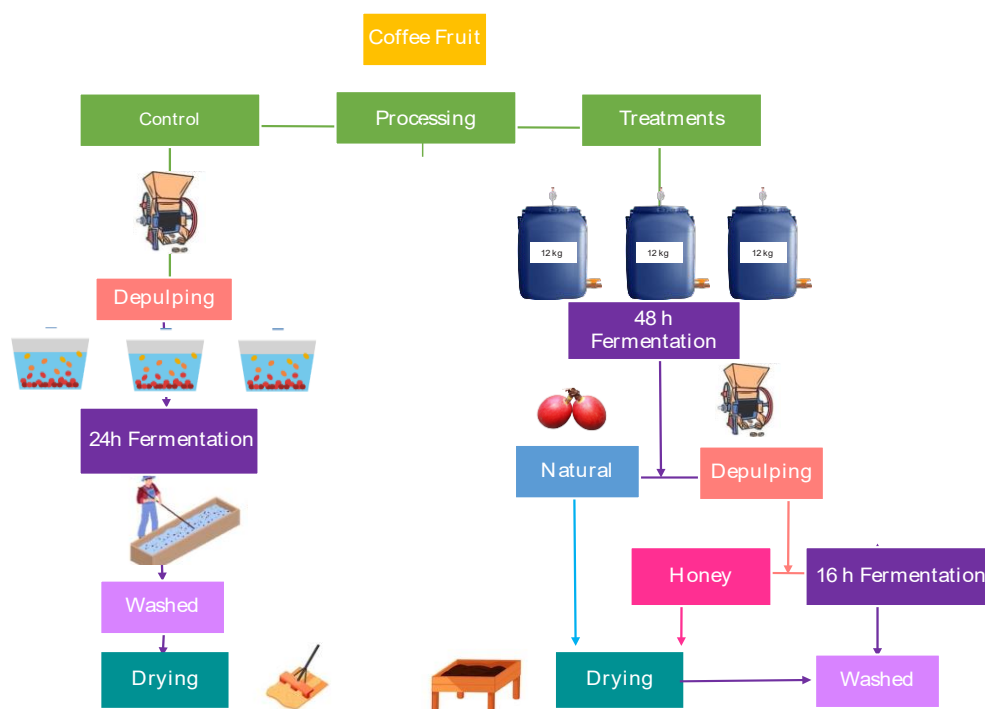
Prior to the training sessions, a meeting was held with the coffee producers of each organization on January 14 and 15, 2021, in which a focus analysis was carried out. Participants expressed their wishes and expectations regarding the training on post-harvest practices, wrote them down, and then shared it with the group. Thus, common objectives were identified, the scope of the training was narrowed down, and the group agreed to work on the importance and improvement of selective harvesting, fermentation and washing, and natural and honey processing practices.

Subsequently, activities were designed for each training session. The first part was carried out in the field, where the topics addressed were selective harvesting and verification of the ripening indexes proposed by the producers. It was also accompanied by the measurement of Brix degrees, for which hand-held refractometers were used, with a measuring range from 0 to 32 % °Bx (Ampro, Mexico). After verifying the ripening indexes, ripe fruits were harvested, collected in baskets, and placed in plastic boxes measuring 51 x 31 x 18 cm, with a capacity of 10 kg. The fruits were taken to the mill and hydraulically sorted using clean, non-recirculated drinking water at a rate of 1.6 L kg<sup>-1</sup> of fruit (Puerta-Quintero, 2015). Floating and damaged fruits were discarded. A sample of 72 kg of freshly cut coffee fruit was available for each formation, provided by the smallholder organizations. In this exercise, the varieties available at the time were used: 1) Bourbon, which is a *Coffea arabica* cultivar highly appreciated in the world coffee arena (World Coffee Research, 2017), is distributed in all coffee growing regions of Mexico and is the most cultivated variety in Chiapas, particularly by small-scale producers (Santoyo-Cortés *et al.*, 1994); 2) Caturra, a low-bearing variety with good yield potential and standard quality in Central America (World Coffee Research, 2017); and 3) Oro Azteca, a low-bearing, high-yielding variety of medium to good cup quality (Escamilla-Prado *et al.*, 2015) generated in Mexico by the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) (World Coffee Research, 2017).

Fermentation exercises were carried out in all the training sessions. In each treatment, three replicates and a control were carried out, which corresponded to a 24 h mucilage fermentation. This procedure is practiced by 90 % of coffee growers in Mexico (Moguel and Toledo, 2004), mainly by those who produce washed raw coffee. For this purpose, samples were taken from the fruits harvested at the beginning and at the end of fermentation. A potentiometer (model Hi98107, Hanna Instruments, Mexico) was used to obtain pH data. To measure electrical conductivity, a conductivity meter with a measurement range of 0–9999 µS cm<sup>-1</sup> and precision ± 2 % (model Hi98130, Hanna Instruments, Mexico) was used. Also, a total dissolved solids (TDS) meter with a range of 0–9999 ppm (model Hi98130, Hanna Instruments, Mexico) and a thermometer to record temperature (model Hi98501, Hanna Instruments, Mexico) were used.

For the fermentation exercises, we worked in a first phase with the coffee fruit in drupe. A total of 12 kg was deposited in high-density polyethylene containers with a capacity of 18 kg of complete coffee fruit. Airlock valves were placed on the lids of the containers to prevent the entry of oxygen but to allow the exit of gases. In this first phase, fermentation was suspended for 48 h (di Cagno *et al.*, 2013).

After the first fermentation phase, the three containers were uncovered to remove the coffee berries, which were divided into three equal parts. The first part was used to dry the whole fruit and obtain a natural coffee; in the second part, the fruits were pulped and placed in sieves to obtain honey coffees; and the third part was pulped and left to ferment in the same containers for 16 h until the detachment of the mucilage, to obtain a washed coffee (Peña and Arango, 2009). After fermentation, the coffees were dried in sieves, in thin layers for better drying, until they reached humidity values between 10 and 12 % (Figure 1).



**Figure 1.** Coffee processing scheme carried out in the post-harvest practices training workshops in Chiapas, Mexico.

After drying, samples were sent to the cupping laboratories of each organization since one of the purposes of the workshops was for the producers to find the best processing for their conditions and varieties. The producers participating in the processing were invited to taste the coffees obtained in the different workshops. Each sample for

tasting consisted of five 150 mL cups, and 10 variables (cup attributes) were evaluated and rated according to the SCA standard on an ordinal scale from 0 to 10 (SCA, 2015). Descriptive analyses were used for the sensory quality of the processes. Analyses of variance (ANOVA) were obtained using R software (version 4.2.2) in a completely randomized design with an equal number of observations ( $n = 12$ ), three treatments, one control, and three replicates. The experimental units were coffees in polyethylene containers with a capacity of 18 kg of coffee fruit.

## RESULTS AND DISCUSSION

For the selective harvesting exercise, participants presented the harvesting techniques they were familiar with. Then, each producer made a ripening index (Figure 2A) and indicated which would be the optimal harvesting stage according to their experience (Figure 2B). Subsequently, each index was verified with the help of a hand-held refractometer. It was confirmed that the best technique for harvesting the fruit is one by one, without detaching the petiole from the branches, since this favors coffee quality and facilitates post-harvest work (de Mesquita *et al.*, 2016).



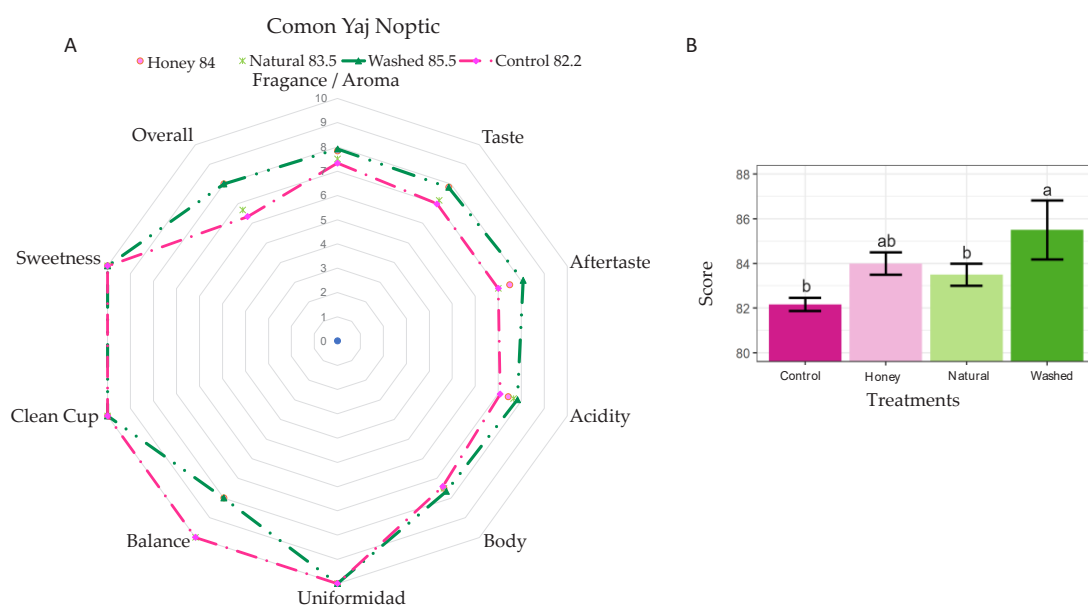
**Figure 2.** Coffee fruit harvest at a suitable stage of maturity. A) ripening index; B) selective harvesting.

It is important to note that different ripening indexes were found, as these depend on environmental conditions and site-specific varieties (Marín-López *et al.*, 2003). In the case of the Comon Yaj Noptic Cooperative, the range of °Bx was between 15 and 19; in Kulaktik Group, between 10 and 13 °Bx; and in the Triunfo Verde Cooperative, between 13 and 21 °Bx.

### Sensory profiles and analysis of variance

The first training was held at the Comon Yaj Noptic Cooperative, where the Red Bourbon variety was used. The notes found by the tasters in the natural processes

were: hazelnut, fruity, molasses, peach, tamarind, lemony, honey, and caramelized sugar, with a medium body and pronounced acidity. In the honey processes, the notes found were: sweet, vanilla, butter, spices, anise, clove, dark chocolate, and milk chocolate, with medium body and medium acidity. For the coffees washed in two fermentation phases, the following were found: chamomile flower, chocolate, maple, and lemony, with a medium body and medium acidity; and for the controls, hazelnut, chocolate, piloncillo, anise, fresh fruit, tamarind, and vegetable flavors were found, with a medium body and pronounced acidity. The sensory quality results reached average scores of 82.2 to 85.5 points, classified as very good on the SCA scale. The best results were obtained with the washed coffees (Figure 3A).

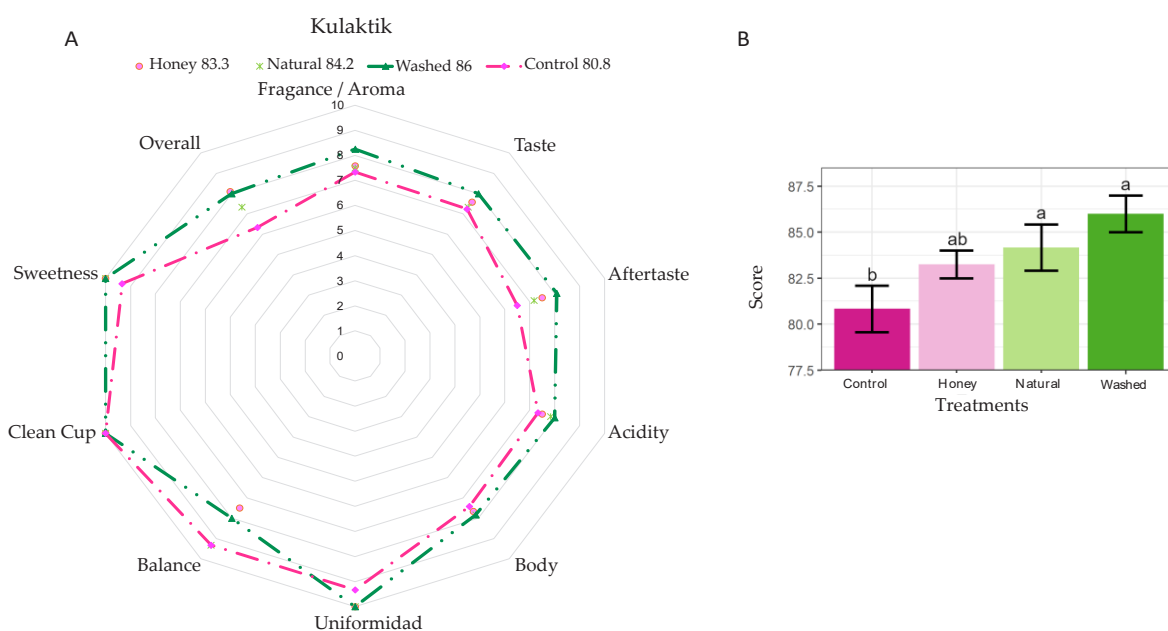


**Figure 3.** A: Coffee sensory profiles generated at the Comon Yaj Noptic Cooperative from three post-harvest processing of coffee beans in Chiapas, Mexico; B: analysis of variance of primary sensory attributes in post-harvest processing. Different letters present a significant statistical difference ( $p < 0.001$ ).

The analysis of variance determined that there were statistically significant differences between the post-harvest processing carried out in the workshop with the Comon Yaj Noptic Cooperative. The greatest difference in quality was obtained in the washing method with a previous fermentation in fruit and then pulping, compared to the control, which involves a traditional washing (Figure 3B).

The second training was conducted with Kulaktik Group, where Bourbon and Caturra varieties were used. The notes found by the tasters in the natural processes were: red fruits, apple, walnut, and milk caramel, with a medium body and malic acidity. In

the honey method, the notes found were: lime, floral, spices, soft caramel, and lemon, with medium body and citric acidity. For the coffees washed in two fermentation phases, the following notes were found: jasmine flowers, chocolate, walnut, maple, soft caramel, and spicy flavor, with a soft, delicate body and pronounced acidity; while for the controls, the following notes were found: ripe fruit, red apple, and mango, with a medium body and pronounced acidity. The sensory quality results reached average scores of 80.8 to 86 points, classified as very good to excellent on the SCA scale (Figure 4A). The best results were obtained by coffees washed in two fermentation phases.

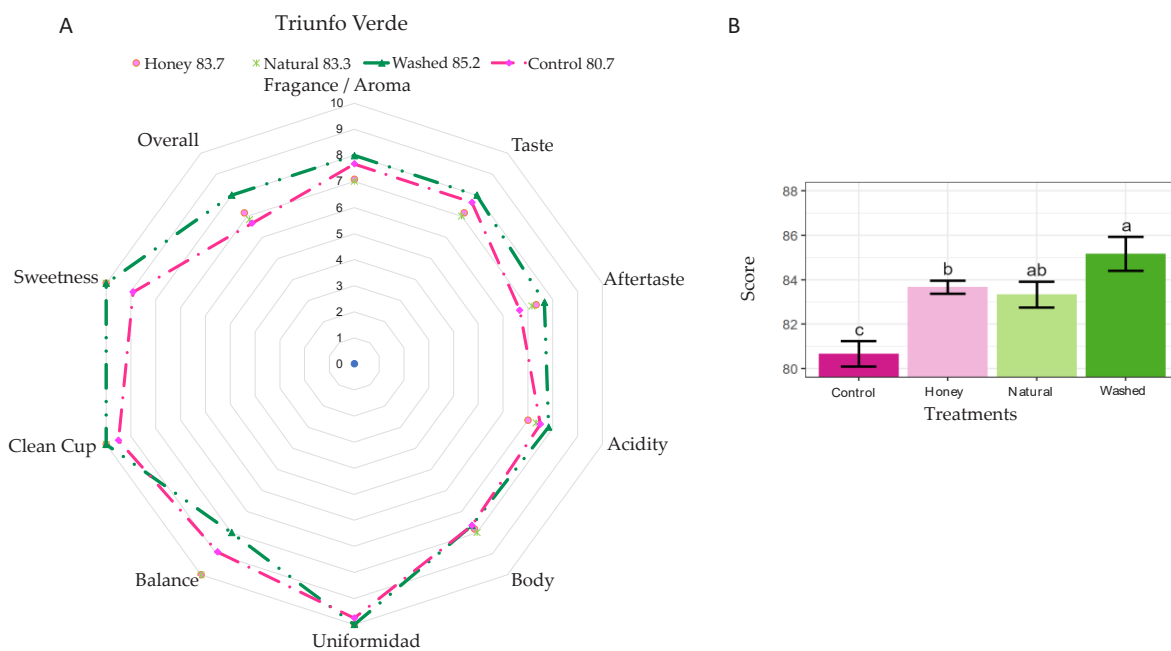


**Figure 4.** A: Coffee sensory profiles generated at the Kulaktik Cooperative from three post-harvest processing of coffee beans in Chiapas, Mexico; B: analysis of variance of primary sensory attributes in post-harvest processing. Different letters present a significant statistical difference ( $p < 0.001$ ).

The analysis of variance showed that there were statistically significant differences between the post-harvest processing carried out in the workshop with the Kulaktik organization. The treatments that showed differences with the control were natural processing and washing after fermentation in fruit (Figure 4B).

The third training was carried out at the facilities of the Triunfo Verde Cooperative, where a blend of Bourbon and Oro Azteca was used. The notes described by the tasters belonging to the association of natural coffee processes were: red fruits, red apple, and plum, with a medium body and high acidity. For the honey processes, the notes found were: chocolate, citrus, ripe fruits, green apple, and lemon, with a light body and medium acidity. In the coffees washed in two fermentation phases, the following

were found: red fruits, cherries, plums, citrus lemon, and red wine, with a medium body and high acidity, balanced and round cup; while in the controls, the following were found: hazelnut, chocolate, piloncillo, anise, fresh fruit, tamarind, and vegetable flavor, with medium body and pronounced acidity. Sensory quality results reached scores averaging 80.7 to 85.2 points, classified as very good on the SCA scale. The best results were obtained by the washed coffees in two fermentation phases (Figure 5A). In the analysis of variance of the scores obtained in the workshop with Triunfo Verde, statistical differences were found between the post-harvest processes, specifically between the washed coffee with pre-fermentation and the control, while the natural processing showed no difference with the control (Figure 5B).



**Figure 5.** A: Sensory profiles of coffee generated at the Triunfo Verde Cooperative from three post-harvest processing of coffee beans in Chiapas, Mexico; B: analysis of variance of primary sensory attributes in post-harvest processing. Different letters show a significant statistical difference ( $p < 0.001$ ).

#### Measurement and control of parameters in fermentation processes.

For the monitoring of parameters during fermentation, pH, electrical conductivity (CE), total dissolved solids (TDS), Brix degrees, and temperature were measured at the beginning and end of the process (Table 1).

At the beginning of the fermentations, a pH between 5.2 and 5.43 was obtained, and participants related the degree of acidity to the maturity of the coffee. Puerta-Quintero (2012) indicates that coffee fruits classified with water after pulping have

**Table 1.** Mean values of parameters recorded at the beginning and end of coffee fermentation carried out in training workshops on post-harvest practices in Chiapas, Mexico.

Organization	Variety	Treatments	pH	Electrical conductivity ( $\mu\text{S cm}^{-1}$ )	TDS* (ppm)	Temperature ( $^{\circ}\text{C}$ )	Brix ( $^{\circ}\text{Bx}$ )
Parameters at the beginning of fermentation							
Comon Yaj Noptic	Red	Natural	5.2	3040	1460	17	16
		Honey	5.4	3350	1956	17	18
	Bourbon	Washed	5.4	3140	1700	18.9	19
Kulaktik	Bourbon/ Caturra	Controls	5.4	2974	1650	18.9	15
		Natural	5.3	2736	1435	23	11
		Honey	5.42	3192	1652	22	12
		Washed	5.5	3238	1843	24	13
Triunfo Verde	Bourbon/ Oro azteca	Controls	5.2	3173	1689	23	13
		Natural	5.43	3457	2907	27.5	17
		Honey	5.3	3814	3143	28	18
		Washed	5.43	3732	3049	28.5	21
		Controls	5.4	3623	1678	26	13
Parameters at the end of fermentation							
Comon Yaj Noptic	Red Bourbon	Natural	3.9	5168	3358	17	2
		Honey	3.8	5695	4499	16	1
		Washed	3.8	5338	3910	17	2
		Controls	3.8	5056	3795	18	3
Kulaktik	Bourbon/ Caturra	Natural	3.7	4651	3301	22	2
		Honey	3.6	5426	3800	21	1
		Washed	3.8	5505	4239	23	3
Triunfo Verde	Bourbon/ Oro azteca	Controls	3.5	5394	3885	23	1
		Natural	3.4	5877	6686	27	2
		Honey	3.7	6484	7229	24	3
		Washed	3.6	6344	7013	26	2
		Controls	3.7	6159	3859	26	2

an average pH value of 5.4, which coincides with what was found in the sampling. In addition, workshop participants considered that the decrease in pH was due to the transformation of compounds in the coffee mucilage. This conclusion is in line with references found in the literature, pointing out that the decrease in pH is due to microbial metabolism during fermentation, where organic acids are produced when decomposing the coffee mucilage, which causes the pH to decrease (de Carvalho *et al.*, 2017; Evangelista *et al.*, 2015). The decision on when to end fermentations was made according to the experience of the producers. At that time, pH values of 3.4 to 3.9 were found, which agrees with Velmourougane (2013), who estimated that the fermentation end point can be determined by the decrease of the pH of the coffee mass from 5.5 to 3.5.

Temperatures at the beginning of fermentation ranged from 17 to 28° C, and at the end, from 16 to 27° C (Table 1). Participants agreed that this variable depends on the location and environmental conditions where coffee processing is carried out. Participants explained that in their experience, there is an inversely proportional relationship between temperature and fermentation time. This coincides with Liu *et al.* (2016), who point out that fermentation temperature not only affects the time of the process, but also exerts a marked effect on the metabolic rate of the microorganisms that can affect the organoleptic properties of the fermented product.

The coffee processed at the lowest temperatures was the one made at Comon Yaj Noptic, with values from 17 to 16° C during the fermentation process. After 48 h, an average pH of 3.8 was obtained (Table 1). According to Puerta-Quintero (2012), the pH of the mucilage depends on the temperature in the system. In contrast, the coffee processed in Triunfo Verde had the highest temperature conditions, starting fermentation at 28° C with a pH value of 5.43. After 48 h, fermentation was interrupted, and a temperature of 27° C and a pH value of 3.4 were recorded. This result agrees with the FAO (2006) report, which argues that time and temperature are crucial parameters of the fermentation process in coffee processing.

The participants related the Brix degrees of coffee mucilage to the concentration of sugars contained in the fruits and, in turn, to the degree of maturity. The Brix degrees recorded at the beginning of the fermentations ranged from 13 to 21 °Bx, but at the end, a drastic reduction in the values was found, obtaining between 1 and 3 °Bx (Table 1). This was attributed, according to the participants, to the transformation of sugars into acids and alcohols, among other compounds. This agrees with de Carvalho *et al.* (2017) and Elhali *et al.* (2020), who reported in different studies that the reduction of sugars during fermentation is accompanied by the accumulation of acids, such as lactic acid, acetic acid, and succinic acid, which are formed due to the action of microorganisms that use sugars as a carbon source for their growth.

The coffee with the lowest °Bx value was found in the workshop with Kulaktik Group (11 °Bx), although the selected coffee presented a crimson red coloration. This was attributed to the presence of rain during harvesting, since relative humidity and the amount of rain are also factors that inversely affect this parameter. This differs from what was proposed by Puerta-Quintero (2012), who states that lower average values are recorded in the mucilage of pinto coffee (14.1 %), ripe coffee (17.1 %), and overripe coffee (20.1 %), which will depend on the agro-climatic conditions of each producing region.

The CE parameter is an indicator for the evaluation of the state of maturity and quality of the fruit (Rehman *et al.*, 2011), information that was shared with the producers. This variable was measured before the beginning and at the end of the fermentation processes, and an increase was observed. Paquet *et al.* (2000) mentioned that changes in CE and pH values during fermentation are closely related and that the former could be used to follow acidification during fermentation. Likewise, Loo-Miranda *et al.* (2022) reported that the CE of whole cocoa beans with shells at the beginning of the

process limits the migration of ions into solution; therefore, the CE had a lower value than fermented unshelled beans, but as fermentation progresses, the number of ions in solution increases, resulting in a higher CE value. This coincides with what was found in the different processes carried out in this work, where the value of the CE at the beginning was lower in the processing of natural coffees containing the husk and higher in those in which the husk was removed, as in the washed and honey processes. The TDS were measured before and at the end of the fermentations, where an increase was also observed because it is one of the most relevant parameters in anaerobic digestion due to the movement and growth of bacteria and the ease of dissolution and transport of nutrients (Sadaka and Engler, 2003). In general, TDS increase during fermentative processes (Mariyam *et al.*, 2022). Likewise, Mariyam *et al.* (2022) found that fermentation TDS are inversely proportional to the pH of coffee beans. TDS are the sum of the compounds, essentially sugars and pectic substances, of coffee dissolved in water (Avallone, 2001). Most of the fermentation studies only report the number of Brix degrees without considering the behavior of the TDS; for this reason, there is little information on this parameter.

The best result in the sensory evaluations was obtained for coffees with washed processes, selective harvest, two fermentation phases, 48 h of fermentation in drupe, and 16 h of pulped fermentation. These achieved scores on the SCA scale of 85.2 with Triunfo Verde, 85.5 with Comon Yaj Noptic, and 86 with Kulaktik. These results were mainly due to the selective harvesting of ripe fruits, which coincides with the observations by Mazzafera and Purcino (2004), where coffees from wet processing presented better quality. The sensory characteristics were mainly attributed to the fact that only fully ripe coffee cherries are used for wet processing (Knopp *et al.*, 2006).

In the different types of fermentation, an increase of 3 to 6 points was observed in selected coffees compared to the controls without selection at harvest (Table 1). Similarly, Ramos *et al.* (2019) found that the best score was obtained from samples of coffee growers who promote selective harvesting, processing, and adequate drying.

On the other hand, producers correctly identified the most important parameters for monitoring. They indicated that, for them, the most important are pH, °Bx, and average temperature, variables that are linked to the fermentation process. In participatory research, without the integrated, conscious, and harmonious participation of all those involved, it is impossible to achieve transformation (Espinoza-Freire, 2020). This work linked the experience of coffee producers in the collective application of techniques for processing organic coffee, which seek to innovate in post-harvest processes to obtain higher quality and, consequently, a better price and thus expand the options for improving the livelihoods of shade-grown coffee-producing families.

## CONCLUSIONS

Selective harvesting is important in post-harvest processes. It is indispensable to create maturity indexes to harvest ripe fruits according to the variety being used, selecting

before processing the coffee by removing green, dry, and severely damaged fruits by berry borer and vain fruits. This practice helps to ensure the quality of subsequent processes. Producers were able to experience the preparation of different processes and verify their results through a sensory exercise. In addition, the intervention of the people involved in the processes was promoted to improve the quality and traceability of the coffee.

Statistically significant differences were found between the different types of post-harvest processing in the exercises conducted in all cooperatives. The coffees scored higher than 85 points and had very good to excellent quality, according to the Specialty Coffee Association protocol, which increases their opportunity to access niche markets. The washed processes obtained the highest score; however, natural and honey processes are a good alternative for those producers who lack water during harvest.

#### ACKNOWLEDGEMENTS

The authors thank the organic coffee producer organizations: Triunfo Verde, Comon Yaj Noptic, and Kulaktik Group for their participation in the information gathering process; Colegio de Postgraduados; and the Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCyT) for their institutional and financial support given to carry out this research.

#### REFERENCES

- Aristizabal-Arias C, Duque-Orrego H. 2006. Determinación de economías de escala en el proceso de beneficio del café en Colombia. *Cenicafé* 57 (1): 17–30.
- Avallone S, Guyot B, Brillouet JM, Olguin E, Guiraud JP. 2001. Microbiological and biochemical study of coffee fermentation. *Current Microbiology* 42 (4): 252–256. <https://doi.org/10.1007/s002840110213>
- de Carvalho NDP, de Melo PG, Tanobe V, Thomaz SV, da Silva BG, Rodrigues C, Soccol C. 2017. Yeast diversity and physicochemical characteristics associated with coffee bean fermentation from the Brazilian Cerrado Mineiro region. *Fermentation* 3 (1): 11. <https://doi.org/10.3390/fermentation3010011>
- de Mesquita CM, de Rezende JE, Carvalho JS, Fabri Júnior MA, Moraes NC, Dias PT, de Carvalho RM, de Araújo WG. 2016. Manual do café: colheita e preparo. Emater-MG: Belo Horizonte, Brasil. 56 p.
- di Cagno R, Coda R, de Angelis M, Gobbetti M. 2013. Exploitation of vegetables and fruits through lactic acid fermentation. *Food Microbiology* 33 (1): 1–10. <https://doi.org/10.1016/j.fm.2012.09.003>
- Elhalis H, Cox J, Zhao J. 2020. Ecological diversity, evolution and metabolism of microbial communities in the wet fermentation of Australian coffee beans. *International Journal of Food Microbiology* 321: e108544. <https://doi.org/10.1016/j.ijfoodmicro.2020.108544>
- Escamilla-Prado E, Ruiz-Rosado O, Zamarripa-Colmenero A, González-Hernández VA. 2015. Calidad en variedades de café orgánico en tres regiones de México. *Revista de Geografía Agrícola* 55: 45–55.

- Escamilla-Prado E. 2012. La calidad del café orgánico en México. Factores ambientales, genéticos, agronómicos y sociales. Editorial Academia Española: Saarbrücken, Alemania. 380 p.
- Escamilla-Prado E. 2016. Las variedades de café en México ante el desafío de la roya, una red para salvar la sombra de la Sierra Madre de Chiapas. Campaña a favor de los acervos de carbono y la biodiversidad en cafetales bajo sombra. Breves de Políticas Públicas. Boletín Informativo. Programa Mexicano del Carbono. Universidad Autónoma Metropolitana: Ciudad de México, México. 10 p.
- Espinoza-Freire EE. 2020. Reflexiones sobre las estrategias de investigación acción participativa. *Conrado* 16 (76): 342–349.
- Evangelista SR, Miguel MG da CP, Silva CF, Pinheiro ACM, Schwan RF. 2015. Microbiological diversity associated with the spontaneous wet method of coffee fermentation. *International Journal of Food Microbiology* 210: 102–112. <https://doi.org/10.1016/j.ijfoodmicro.2015.06.008>
- FAO (Food and Agriculture Organization). 2006. Enhancement of coffee quality through the prevention of mould formation. Food and Agriculture Organization. Common Fund for Commodities. Government of the Netherlands. International Coffee Organization. Rome, Italy. [https://www.fao.org/fileadmin/user\\_upload/agns/pdf/coffee/FTR2006.pdf](https://www.fao.org/fileadmin/user_upload/agns/pdf/coffee/FTR2006.pdf) (Retrieved: September 2022).
- Knopp S, Bytof G, Selmar D. 2006. Influence of processing on the content of sugars in green Arabica coffee beans. *European Food Research and Technology* 223 (2): 195–201. <https://doi.org/10.1007/s00217-005-0172-1>
- Liu D, Zhang H, Lin C, Xu B. 2016. Optimization of rice wine fermentation process based on the simultaneous saccharification and fermentation kinetic model. *Chinese Journal of Chemical Engineering* 24 (10): 1406–1412. <https://doi.org/10.1016/j.cjche.2016.05.037>
- Loo-Miranda JLM, Chire-Fajardo GC, Ureña-Peralta MO. 2022. Correlation between electrical conductivity and the percentage of fermented beans for Peruvian CCN 51 cocoa beans. *Ingeniería e Investigación* 42 (3): e206. <https://doi.org/10.15446/ing.investig.92556>
- Magalhães Júnior AI, de Carvalho NDP, de Melo PGV, da Silva VA, Medina JDC, de Carvalho JC, Soccol CR. 2021. A critical techno-economic analysis of coffee processing utilizing a modern fermentation system: Implications for specialty coffee production. *Food and Bioprocess Processing* 125: 14–21. <https://doi.org/10.1016/j.fbp.2020.10.010>
- Marín-López SM, Arcila-Pulgarín J, Montoya-Restrepo EC, Oliveros-Tascón CE. 2003. Cambios físicos y químicos durante la maduración del fruto de café (*Coffea arabica* L. var. Colombia). *Cenicafé* 54 (3): 208–225.
- Mariyam S, Kistanti A, Karyadi JNW, Widiyastuti RJ. 2022. Improving coffee quality through yeast addition in the fermentation process to support sustainable coffee production. *IOP Conference Series: Earth and Environmental Science* 1005 (1): 012012. <https://doi.org/10.1088/1755-1315/1005/1/012012>
- Mazzafera P, Purcino RP. 2004. Post-harvest processing methods and physiological alterations in the coffee fruit. *In* 20th International Scientific Colloquium on Coffee. Association for Science and Information on Coffee: Bangalore, India, pp: 811–819.
- Moguel P, Toledo VM. 2004. Conservar produciendo: biodiversidad, café orgánico y jardines productivos. *Biodiversitas* 55: 1–7.
- Paquet J, Lacroix C, Audet P, Thibault J. 2000. Electrical conductivity as a tool for analysing fermentation processes for production of cheese starters. *International Dairy Journal* 10 (5–6): 391–399. [https://doi.org/10.1016/S0958-6946\(00\)00060-1](https://doi.org/10.1016/S0958-6946(00)00060-1)

- Peña C, Arango R. 2009. Evaluación de la producción de etanol utilizando cepas recombinantes de *Saccharomyces cerevisiae* a partir de melaza de caña de azúcar. *Dyna* 76 (159): 153–161.
- Poltronieri P, Rossi F. 2016. Desafíos en el procesamiento de cafés especiales y aseguramiento de la calidad. *Challenges* 7 (2): 19. <https://doi.org/10.3390/challe7020019>
- Puerta-Quintero GI. 2000. Beneficie correctamente su café y conserve la calidad de la bebida. Centro Nacional de Investigaciones del Café: Manizales, Colombia. 8 p.
- Puerta-Quintero GI. 2012. Factores, procesos y controles en la fermentación del café. Centro Nacional de Investigaciones del Café: Manizales, Colombia. 12 p.
- Puerta-Quintero GI. 2015. Fermentación controlada del café: tecnología para agregar valor a la calidad. Centro Nacional de Investigaciones del Café: Manizales, Colombia. 12 p.
- Ramírez-García A, Camacho-Bercherit M. 2019. Diagnóstico participativo para determinar problemas ambientales en comunidades rurales. *Telos* 21 (1): 86–113.
- Ramos-Cotacallapa E, Lima-Medina I, Cornejo-Condori GB. 2019. Comparativo de calidad organoléptica de café (*Coffea arabica* L.) en Puno (Perú) y La Paz (Bolivia). *Revista de Investigaciones Altoandinas* 21 (4): 283–292. <https://doi.org/10.18271/ria.2019.505>
- Rehman M, Abu IBAJA, Abdullah MZ, Arshad M R. 2011. Assessment of quality of fruits using impedance spectroscopy. *International Journal of Food Science and Technology* 46 (6): 1303–1309. <https://doi.org/10.1111/j.1365-2621.2011.02636>
- Sadaka SS, Engler CR. 2003. Effect of initial total solids on composting of raw manure with biogas recovery. *Compost Science and Utilization* 11 (4): 361–369. <https://doi.org/10.1080/1065657X.2003.10702146>
- Santoyo-Cortés V, Diaz-Cárdenas S, Rodríguez-Padrón B, Pérez-Pérez JR, Sosa-Maldonado R, Robledo-González L, Licona-Vargas A. 1994. Sistema agroindustrial café en México: diagnóstico, problemática y alternativas. Universidad Autónoma Chapingo: Chapingo, México. 157 p.
- SCA (Specialty Coffee Association of America). 2015. SCA protocols - Cupping specialty coffee. Irvine, CA, USA. <https://sca.coffee/research> (Retrieved: April 2024).
- Velmourougane K. 2013. Impact of natural fermentation on physicochemical, microbiological and cup quality characteristics of Arabica and Robusta coffee. *Proceedings of the National Academy of Sciences, India Section B. Biological Sciences* 83 (2): 233–239. <https://doi.org/10.1007/s40011-012-0130-1>
- World Coffee Research. 2017. Las variedades de café de Mesoamérica y el Caribe. Portland, OR, USA. <https://varieties.worldcoffeeresearch.org/> (Retrieved: October 2022).

## ORCHID DIVERSITY (Orchidaceae) IN TWO URBAN SITES IN THE STATE OF VERACRUZ, MEXICO

Obdulia Baltazar-Bernal<sup>1\*</sup>, Jesús Zavala-Ruiz<sup>2</sup>, Arturo Hernández-García<sup>1</sup>

<sup>1</sup>Colegio de Postgraduados Campus Córdoba. Carretera Córdoba-Veracruz km 348, Amatlán de los Reyes, Veracruz, Mexico. C. P. 94953.

<sup>2</sup>Universidad Autónoma Metropolitana Unidad Iztapalapa. Departamento de Economía. Av. Ferrocarril San Rafael Atlixco no. 186, Col. Leyes de Reforma 1a. Sección, Iztapalapa, Mexico City, Mexico. C. P. 09310.

\* Author for correspondence: obduliabb@colpos.mx

### ABSTRACT

Knowledge of urban orchids and their phorophytes is essential for conservation and education initiatives in these areas. The objective of this study was to assess the diversity of epiphytic orchids and identify their phorophytes at Postgraduate College Campus Córdoba (CPCC) and Paso Coyol Ecological Park (PEPC) in order to better understand the differences in their composition. The hypothesis was that the diversity of naturally established orchids would be higher in the less urbanized area, while the phorophytes would be mostly introduced trees. Orchids growing on phorophytes of the garden area (12 000 m<sup>2</sup>) of both sites were quantified from November 2019 to December 2021. The origin (endemic, native, or exotic) of the orchids and their phorophytes were determined. Simpson and Shannon-Weaver diversity indices were applied, and Whittaker curves were developed. A total of 13 419 orchid individuals were recorded, divided into 31 species, with 26 species reported in the CPCC and 17 in the PEPC. The Simpson and Shannon-Weaver indices showed that the diversity of epiphytic orchids was higher in the CPCC (1-D = 0.78) than in the PEPC (1-D = 0.41). In contrast, species dominance was lower in the CPCC (H = 2.6) than in the PEPC (H = 1.16). Whittaker curves showed that *Catasetum integerrimum* was the most abundant species in the CPCC and *Platystele stenostachya* in the PEPC. The CPCC had a greater level of diversity. Fifteen species of phorophytes were recorded in the CPCC and 10 in the PEPC, with a predominance of exotic species, while introduced species accounted for 70 % of the phorophytes found.

**Keywords:** urban flora, native orchids, urban gardens, green spaces, host tree.

### INTRODUCTION

The growth of cities and changes in land use have decreased the size of natural ecosystems, causing the loss of habitats and species in occupied spaces (de Oliveira *et al.*, 2011). Cities have become study systems for urban ecology, integrating theories and methods from the natural and social sciences with the intention of studying the patterns and processes of urban ecosystems (Cursach *et al.*, 2012). This allows for

**Citation:** Baltazar-Bernal O, Zavala-Ruiz J, Hernández-García A. 2024. Orchid diversity (Orchidaceae) in two urban sites in the state of Veracruz, Mexico. *Agrociencia* 58(5): 571-583. <https://doi.org/10.47163/agrociencia.v58i5.3125>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: December 01, 2023.

Approved: July 04, 2024.

**Published in Agrociencia:**

August 06, 2024.

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



improved understanding of global climate change and how biological and cultural components interact in a particular setting (Redman *et al.*, 2004).

In cities, green areas are made up of parks, gardens, and tree-lined streets and avenues, where humans interact with biological diversity. These spaces have the appropriate conditions for the survival of several species (Lara *et al.*, 2017). Green spaces beautify cities, serve as indicators of the environmental quality of the urban ecosystem, improve the quality of life of their inhabitants, and fulfill their productive, social, and environmental functions (Córdova-Stroobandt, 2013). The planning of green spaces is generally based on aesthetic and economic perspectives, using mostly fast-growing, low-cost, shade-producing ornamental flora (González-Ball *et al.*, 2017; Lara *et al.*, 2017).

A mix of native and exotic species from various evolutionary and geographic origins make up urban flora. For example, the flora of European cities presents a higher composition of native species, whereas in the Americas exotic species dominate (Castro *et al.*, 2018). Exotic flora normally causes negative effects on native flora since some species can compete with and parasitize native plants, affecting their development and reproduction, modifying the abiotic conditions of the site, and generating unnecessary shade to other plants and allelopathy (Carvallo, 2009).

Within the epiphyte group, the Orchidaceae family is one of the most diverse, with the highest number of endemic species and being the second most threatened in Mexico (Castillo-Pérez *et al.*, 2018; Villaseñor, 2016). In addition, orchids are recognized by commensalism associations with phorophytes (Izuddin *et al.*, 2019). The growth and survival of orchids depend on the availability and characteristics of their phorophytes in their natural habitats and in disturbed environments (Izuddin *et al.*, 2019). In urban green spaces, trees, shrubs, and cycads are used as phorophytes for the natural and assisted establishment of several species of orchids native to Mexico (Baltazar-Bernal *et al.*, 2020). However, despite the importance of epiphytic orchids, there are few reports concerning their diversity in public urban areas (Izuddin *et al.*, 2019; Lussu, 2022; Salazar-Rojas and Mata-Rosas, 2003).

Epiphytes in nearby urban sites may differ (Gomes and Campos, 2019), because urbanization generates a hostile microclimate that has a negative impact on flora diversity (Acosta-Hernández, 2017), related phorophytes (Gomes and Campos, 2019), and pollinators (Newman *et al.*, 2013). Parks and other public places are designed by humans, and some of them are located in large cities and host diverse plant groups. Therefore, these spaces can be considered key sites to carry out the observation, determination, and conservation of orchid diversity.

Based on the above, the objective of this study was to evaluate the diversity of orchids that inhabit the gardens of the Postgraduate College Campus Córdoba (CPCC) and Paso Coyol Ecological Park (PEPC) to know their origin (endemic, native, and introduced) and category of extinction risk, as well as their phorophytes.

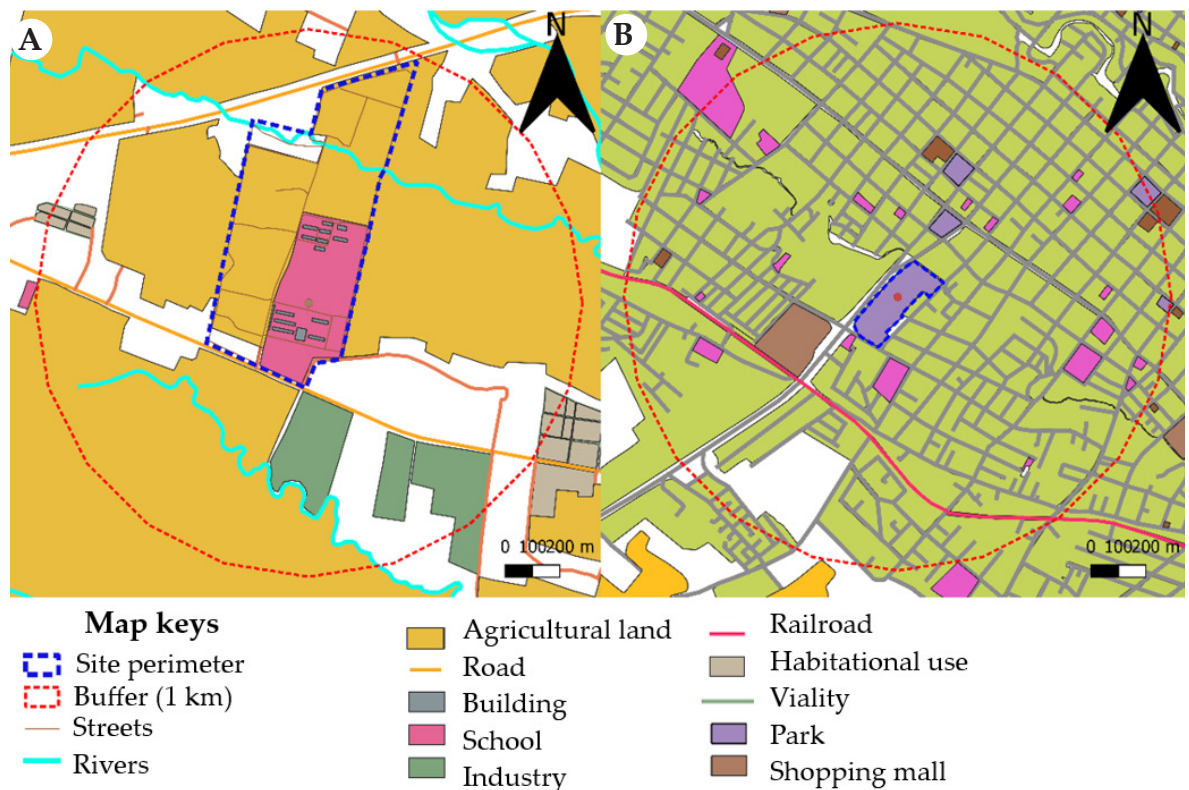
## MATERIALS AND METHODS

### Study sites

Two urban sites were evaluated from November 2019 to December 2021. The first site is located in the garden area of the Postgraduate College Campus Córdoba (CPCC), located in the municipality of Amatlán de los Reyes, Veracruz, Mexico ( $18^{\circ} 51' 21''$  N and  $96^{\circ} 51' 35''$  W), at an altitude of 647 m (Figure 1). The climate in this site is warm-humid, with abundant rainfall in summer (INEGI, 2008), a mean annual temperature of  $20^{\circ}\text{C}$  (INEGI, 2007), and a mean total annual precipitation of 1900 mm (INEGI, 2006). The CPCC gardens are open areas with less than 50 % tree cover surrounding the research center buildings. These gardens occupy an area of 18 000 m<sup>2</sup>. The land surrounding the CPCC is mostly used for sugar cane cultivation, followed by industrial use. There are also two streams, roads, and areas for residential use (Figure 2A). The second site evaluated was the Paso Coyol Ecological Park (PEPC), which has an area of 45 000 m<sup>2</sup> and is located in Córdoba, Veracruz, Mexico ( $18^{\circ} 53' 26''$  N and  $96^{\circ} 56' 35''$  W), at an altitude of 915 m (Figure 1). The climate is semi-warm and humid with abundant rainfall in summer (INEGI, 2008), a mean annual temperature of  $21^{\circ}\text{C}$  (INEGI, 2007), and a mean annual total of 2000 mm (INEGI, 2006). The PEPC has 80 % (36 000 m<sup>2</sup>) of green areas and the rest of the space is occupied by buildings



**Figure 1.** Geographical location of Postgraduate College Campus Córdoba, in Amatlán de los Reyes, Veracruz, Mexico, and Paso Coyol Ecological Park, in Córdoba, Veracruz, Mexico.



**Figure 2.** Zoning and land use around the study areas. A: Postgraduate College Campus Córdoba, in Amatlán de los Reyes, Veracruz, Mexico; B: Paso Coyol Ecological Park, in Córdoba, Veracruz, Mexico.

(auditorium, warehouse, public restrooms, exhibition area, administrative area, ticket office, and parking lot). The surrounding area of the PEPC is mainly occupied by residential areas with few green areas around it (Figure 2B).

### Sampling of orchids and phorophytes

The orchid and phorophyte census were carried out in the gardens of the CPCC and the green areas of the PEPC (Figure 1). To register the number of orchids of each species, one plant (an individual with one or a group of pseudobulbs) was considered, except *Vanilla planifolia* and *Epidendrum radicans*, which are monopodic in growth. Epiphytic orchid individuals were quantified in each of the phorophytes (trees, shrubs, palms, and a *Zamia*). In addition, for each phorophyte, the species to which it belongs was recorded. For the determination of the orchid species, different bibliographic sources were consulted (García-Cruz *et al.*, 2003; Hágsater *et al.*, 2005; Soto-Arenas *et al.*, 2005). Also, the identification was corroborated with specialists in systematics of the Orchidaceae family. To determine its conservation status, NOM-059 (DOF, 2010) was consulted.

### Data analysis

To determine orchid diversity, only species that conserve natural populations were used, which are those that existed in the site prior to human intervention or colonized the trees without the need for human intervention. The diversity index (Simpson, 1945) was used, using the equation:

$$1 - \sum_{i=1}^N p_i^2$$

where  $p_i$  represents the proportion or relative abundance of each species, from 1 to the umpteenth ( $i = 1, 2, 3, \dots, N$ ) species in the population. This index measures the probability that two individuals from a sample taken at random belong to different species; its values range from 0 to 1. In addition, the Shannon-Weaver index was used (Shannon and Weaver, 1949), which measures the average degree of uncertainty in predicting to which species an individual will belong in a random sample by means of the equation:

$$H' = - \sum_{i=1}^N p_i \log_2 p_i$$

where  $p_i$  measures the average degree of uncertainty in predicting to which species a randomly chosen individual from a sample will belong.

## RESULTS AND DISCUSSION

### Epiphytic orchids

A total of 13 419 individuals were recorded, distributed across 24 genera and 31 species, of which 26 were found in the CPCC and 17 in the PEPC (Table 1). Nine orchid species (*Encyclia parviflora*, *Gongora galeata*, *Lycaste aromatica*, *Maxillaria densa*, *Maxillaria elatior*, *Myrmecophila grandiflora*, *Restrepia ophiocephala*, *Specklinia digitale*, and *Trichocentrum lindenii*) are endemic species; 21 are native to Mexico, and only *Dendrobium nobile* is introduced. *Guarianthe skinneri*, *Specklinia digitale*, and *Stanhopea oculata* are classified as threatened (A), while *Vanilla planifolia* is considered under special protection (Pr) (DOF, 2010).

According to the Simpson's diversity index, the diversity of epiphytic orchids was higher in the CPCC ( $1 - D = 0.75$ ) than in the PEPC ( $1 - D = 0.4$ ). The Simpson's dominance index (D) was higher in the PEPC ( $D = 0.59$ ), indicating a higher dominance by one species (*Platystele stenostachya* with 9673 individuals), compared to the CPCC, which indicates a lower dominance ( $D = 0.22$ ). According to the Shannon-Weaver

**Table 1.** Epiphytic orchids species found in the gardens of the Postgraduate College Campus Córdoba (CPCC) and Paso Coyol Ecological Park (PEPC), in Veracruz, Mexico.

Number	Species	Establishment	Individuals	
			CPCC	PEPC
1	<i>Brassia verrucosa</i> Lindl.	⌘	3	---
2	<i>Catasetum integerrimum</i> Hook.	P	157	5
3	<i>Coelia macrostachya</i> Lindl.	⌘	1	---
4	<i>Dendrobium nobile</i> Lindl.	⌘	---	2
5	<i>Encyclia parviflora</i> (Regel) Withner <sup>†</sup>	P	3	---
6	<i>Epidendrum cardiophorum</i> Schltr.	P	1	---
7	<i>Epidendrum ciliare</i> Jacq.	P	1	---
8	<i>Epidendrum radicans</i> Pav. ex Lindl.	P, ⌘	10	1
9	<i>Gongora galeata</i> Lindl. <sup>†</sup>	⌘	---	1
10	<i>Guarianthe skinneri</i> (Bateman) Dressler & W.E. Higgins <sup>§</sup>	⌘	---	7
11	<i>Laelia anceps</i> Lindl.	⌘, P	6	14
12	<i>Lycaste aromatica</i> (Graham.) Lindl. <sup>†</sup>	⌘	2	---
13	<i>Maxillaria densa</i> Lindl. <sup>†</sup>	P	4	21
14	<i>Maxillaria lineolata</i> (Fenzl Molinari)	⌘	---	1
15	<i>Maxillaria elatior</i> Rchb. f. <sup>†</sup>	P	2	---
16	<i>Maxillaria variabilis</i> Bateman ex Lindl.	⌘	2	---
17	<i>Myrmecophila grandiflora</i> (Lindl.) Carnevali, Tapia-Muñoz & I. Ramírez <sup>†</sup>	P, ⌘	10	---
18	<i>Notylia barkeri</i> Lindl.	P	28	---
19	<i>Oncidium sphacelatum</i> Lindl.	⌘	105	44
20	<i>Platystele stenostachya</i> (Rchb. f.) Garay	P	1	9673
21	<i>Prosthechea ochracea</i> (Lindl.) W.E. Higgins	⌘	9	---
22	<i>Prosthechea radiata</i> (Lindl.) W.E. Higgins	⌘	20	8
23	<i>Restrepia ophiocephala</i> (Lindl.) Garay & Dunst <sup>†</sup>	P	---	286
24	<i>Rhynchoaelia glauca</i> (Lindl.) Schltr.	⌘	1	7
25	<i>Specklinia digitale</i> (Luer) Pridgeon & M.W. Chase <sup>†</sup>	P	18	984
26	<i>Specklinia tribuloides</i> (Sw.) Pridgeon & M.W. Chase	P	20	1854
27	<i>Stanhopea oculata</i> (G.Lodd.) Lindl. <sup>§</sup>	⌘	1	---
28	<i>Trichocentrum lindenii</i> (Brongn.) M.W. Chase & N.H. Williams <sup>†</sup>	P	60	---
29	<i>Trichocentrum luridum</i> (Lindl.) M.W. Chase & N.H. Williams	P	82	10
30	<i>Trichosalpinx ciliaris</i> (Lindl.) Luer.	⌘	1	---
31	<i>Vanilla planifolia</i> Jacks. <sup>¶</sup>	⌘	1	2

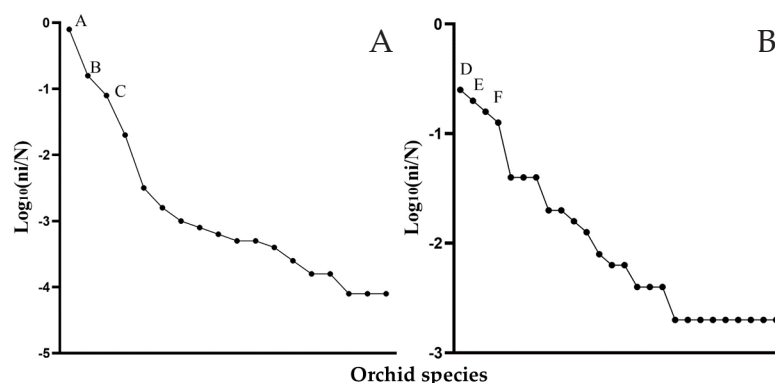
<sup>†</sup>Endemic species; <sup>¶</sup>species under special protection (Pr); <sup>§</sup>threatened species, according to NOM-059-SEMARNAT-2010 (DOF, 2010). <sup>P</sup>Naturally established plant; <sup>⌘</sup>human-established plant.

index, species diversity was higher in the CPCC ( $H' = 2.24$ ) than in the PEPC ( $H' = 1.14$ ) (Table 2).

Regarding the relative abundance of orchids, the abundance range or Whittaker curves showed that *Catasetum integerrimum* was the most abundant species in the CPCC and *Platystele stenostachya* in the PEPC (Figure 3).

**Table 2.** Diversity indices of naturally established orchids in the gardens of the Postgraduate College Campus Córdoba (CPCC) and Paso Coyol Ecological Park (PEPC), in Veracruz, Mexico.

Variables	CPCC	PEPC
Number of species	12	6
Number of individuals	385	12832
Simpson's diversity index	0.75	0.40
Shannon-Weaver's diversity index	2.24	1.14



**Figure 3.** Whittaker range-abundance curves of orchids for the evaluated sites. A: Paso Coyol Ecological Park (PEPC); B: Colegio de Postgraduados Campus Córdoba (CPCC). Letters represent the most abundant species (A: *Platystele stenostachya*, B: *Specklinia tribuloides*, C: *Specklinia digitale*, D: *Catasetum integerrimum*, E: *Oncidium sphacelatum*, F: *Trichocentrum luridum*).

Regarding the origin of the orchids in the CPCC, 12 species were established naturally (46%), while 14 (54%) were established manually. Among the former, *Specklinia digitale* stands out, and among the latter, *Stanhopea oculata*, both under the threatened category (A); *S. oculata* is a native species of the mountain mesophyll forest, with ornamental value (Table 1). In the PEPC, six species (35%) were found to be naturally established, and 11 species (65%) were manually established. Among the former, *S. digitale* stands out, and among the latter, *Guarianthe skinneri* and *Dendrobium nobile*. *S. digitale* is a tiny orchid with large populations and is considered threatened (A). Like *G. skinneri*, it is an introduced species found from the humid forests of Chiapas in Mexico to Panama. *D. nobile* is a species of Asian origin with wide ornamental use in the region (Table 1). The study showed that there are 30 species of orchids native to Mexico, representing approximately 7% of the orchid species in the state of Veracruz and 2.4% of the orchid species of Mexico (Soto-Arenas *et al.*, 2007). One exotic species (*Dendrobium nobile*) was also found (Table 1). This could indicate that the CPCC and the PEPC have favorable

conditions for hosting a large part of the species of the region and other parts of the country, so these areas should be taken advantage of and used as reservoirs of native diversity or sites for the protection of urban orchids. This could be the beginning for utilizing these patches of vegetation in urban environments (Lussu, 2022).

At CPCC and PEPC, 26 and 17 orchid species were found, respectively. These values are lower than the 190 species found in the Soconusco Regional Botanical Garden at the Southern Border College in Tapachula, Chiapas, where they are used for conservation, research, propagation, and dissemination (Damon, 2018); and also lower than the 329 species held by the Clavijero Botanical Garden of the Institute of Ecology in Xalapa, Veracruz, where they are propagated with the purpose of contributing to their conservation (Salazar-Rojas and Mata-Rosas, 2003). However, both the CPCC and the PEPC harbor more species than those reported in the city of Cagliari, Italy (Lussu, 2022).

In the PEPC, *Guarianthe skinneri* was found, which is an orchid native to the southeast of the state of Chiapas, with distribution as far as Panama. This species faces serious problems of intensive and illegal extraction, which has caused a drastic decrease in its populations (Coutiño-Cortés *et al.*, 2018). Thus, it is considered a threatened species according to NOM-059 (DOF, 2010). International trade is regulated by the Convention on International Trade of Endangered Species of Wild Fauna and Flora (CITES), under Appendix II (CITES, 2013).

Manually established orchids represented 54 and 65 % of the species found in the CPCC and the PEPC, respectively, possibly influenced by the aesthetic attributes of the flowers of species such as *Brassia verrucosa*, *Dendrobium nobile*, *Guarianthe skinneri*, *Lycaste aromatica*, *Oncidium sphacelatum*, *Stanhopea oculata*, and *Vanilla planifolia*, known for their high ornamental value (Castillo-Pérez *et al.*, 2018) and for providing an important visual attraction to the landscape.

The Shannon-Weaver and Simpson indices indicated a higher diversity of orchid species in the CPCC than in the PEPC. This difference between sites is due to higher urbanization in the PEPC (Alvim *et al.*, 2020), which may originate an adverse microclimate (Oliván and Volponi, 2012), decreased orchid diversity (Acosta-Hernández, 2017), phorophytes (Alvim *et al.*, 2020), and pollinators, as demonstrated in other studies (Newman *et al.*, 2013). In Colombia, Acosta-Hernández (2017) explains that due to low urbanization, Paseo del Bosque had the highest species richness in flora and a high proportion of native species; he also indicated low urbanization compared to Alberti Park (Oliván and Volponi, 2012).

The presence of orchids in these urban sites requires the monitoring of specimens, their management, and sustainable use so that they are not seriously affected, nor their survival or the loss of genetic material is compromised, preserving the high value of orchids. Urban sites facilitate the recording of the reproductive phenology of the species in order to know the flowering, pollination, and fruiting periods. In addition, it is important to analyze the potential of these spaces as refuges or institutional and public reserves that protect orchids as a valuable natural resource. Urban sites also

facilitate management focused mainly on conservation, as it is important to protect and multiply the species designated in NOM-059-2010 (DOF, 2010), such as *Guarianthe skinneri*, *Specklinia digitale*, *Stanhopea oculata*, and *Vanilla planifolia*.

### Phorophytes

A total of 23 species were recorded, distributed in 19 families: 15 in the CPCC (Table 3), 10 in the PEPC (Table 4), and two in both sites. Only *Dioon edule* was recognized as an endemic species and in the category of endangered (P) according to NOM-059-SEMARNAT-2010 (DOF, 2010). In the CPCC, 53 % of the phorophyte species are exotic. *Azadirachta indica* harbored the highest number of orchid species (10), while *Persea schiedeana* and *Pouteria sapota* were the native phorophytes that harbored more orchid species (six) (Table 3).

In the PEPC, 80 % of exotic species of phorophytes were recorded. *Mangifera indica* hosted the largest number of orchid species (six), with large populations of *Platystele stenostachya*, *Restrepiella ophiocephala*, *Specklinia digitale*, and *Specklinia tribuloides*. On the other hand, *Acrocomia aculeata* was the only native phorophyte species that hosts *Epidendrum radicans* in this park (Table 4).

The diversity of phorophytes reported in this study is important for the establishment and colonization of epiphytic orchids inhabiting the study sites, as indicated by Izuddin *et al.* (2019). In the CPCC, 53 % of the phorophyte population are exotic species, highlighting *Azadirachta indica*, which is widely used for assisted orchid establishment due to its high availability and easy accessibility in the CPCC. It is notorious that

**Table 3.** Phorophyte species present in the gardens of the Postgraduate College Campus Córdoba (CPCC) in Veracruz, Mexico.

Family	Species	Origin	Orchids <sup>†</sup>
Anacardiaceae	<i>Anacardium occidentale</i> L.	Exotic	2,20
Anonaceae	<i>Annona muricata</i> L.	Exotic	2,20
Arecaceae	<i>Phoenix roebelenii</i> O'Brien.	Exotic	2
Asparagaceae	<i>Yucca elephantipes</i> Regel.	Native	2,18,22,23
Boraginaceae	<i>Cordia alliodora</i> (Ruiz & Pav.) Oken.	Native	12,13
Cupressaceae	<i>Thuja occidentalis</i> L.	Exotic	19,29,30
Lauraceae	<i>Persea schiedeana</i> Nees.	Native	2,7,12,14,21
Meliaceae	<i>Cedrela odorata</i> L.	Native	12,13,25
Combretaceae	<i>Combretum</i> sp.	Exotic	20
Moraceae	<i>Ficus macrophylla</i> Desf. ex Pers.	Exotic	2,5,30
Myrtaceae	<i>Psidium guajava</i> L.	Native	20
Meliaceae	<i>Azadirachta indica</i> A. Juss.	Exotic	1,2,3,6,18,20,22,23,28,31
Rutaceae	<i>Citrus x limon</i> (L.) Osbeck	Exotic	5
Sapotaceae	<i>Pouteria sapota</i> (Jacq.) H.E.Moore & Stearn	Native	2,14,16,26,27,29
Zamiaceae	<i>Dioon edule</i> Lindl.*	Native	30

<sup>†</sup>Orchid species (Table 1).

**Table 4.** Phorophyte species in the green areas of the Paso Coyol Ecological Park (PEPC) in Veracruz, Mexico.

Family	Species	Origin	Orchids <sup>†</sup>
Anacardiaceae	<i>Mangifera indica</i> L.	Exotic	2,14,21,24,26,27
Arecaceae	<i>Acrocomia aculeata</i> (Jacq.) Lodd. ex Mart.	Native	8
Bignoniaceae	<i>Spathodea campanulata</i> P. Beauv.	Exotic	10,12,20,23,31
Fabaceae	<i>Delonix regia</i> (Boyer ex Hook.) Raf.	Exotic	2,9,12,20,25
Malvaceae	<i>Hibiscus</i> sp. L.	Exotic	20
Moraceae	<i>Ficus benjamina</i> L.	Exotic	14,20
	<i>Ficus macrophylla</i> Desf. ex Pers.	Exotic	14,19,20
Myrtaceae	<i>Psidium guajava</i> L.	Native	20,32
Rosaceae	<i>Prunus dulcis</i> (Mill.) D.A. Webb.	Exotic	11,12,24
Rutaceae	<i>Citrus x limon</i> Osbeck	Exotic	19,20,31

<sup>†</sup>Orchid species (Table 1).

47 % of native orchid species are naturally hosted on *Persea schiedeana* and *Pouteria sapota*, confirming that they are optimal for orchid colonization and anchorage due to their cracked bark (Izuddin and Webb, 2015). It is clear that both phorophytes can be used to establish orchids obtained from *in vitro* culture to evaluate their adaptation. In addition, being dual-purpose species, as they are fruit trees, it is important to carry out their planting. Thus, urban flora fragments can be considered outdoor laboratories for botany teaching, especially on university campuses (Dávila *et al.*, 2021).

In the PEPC, 90 % of the phorophytes are exotic species, such as *Mangifera indica*, which stands out for hosting large colonies of orchids such as *Platystele stenostachya*, which exceed 9000 individuals naturally established in this host. On the other hand, *Delonix regia* and *Spathodea campanulata* are dangerous species for urban areas due to their thick, shallow, spreading roots and their aggressive growth, which damages hydraulic networks in houses and other constructions (Vargas-Garzón and Molina-Prieto, 2010). According to Lowe *et al.* (2000), *Spathodea campanulata* is on the list of the 100 most damaging invasive species in the world because of its impact on biological diversity and the ease with which it can establish, thrive, and dominate new habitats. For this reason, it is advisable to undertake studies to determine the dominance of this species in the PEPC and to evaluate the impact it has had on other species. Regarding native species of phorophytes, only one specimen of the *Acrocomia aculeata* palm was found, which hosts the *Epidendrum radicans* orchid in its trunk, an orchid of mainly rupicolous habits, but which was established in an assisted manner.

In the two sites studied, the population of exotic phorophytes exceeds native phorophytes, significantly confirming human intervention in these urban spaces, based mainly on ornamental criteria (González-Ball *et al.*, 2017; Lara *et al.*, 2017) rather than on the biological importance of native species in the landscape (Ruas *et al.*, 2022).

## CONCLUSIONS

The Colegio de Postgraduados Campus Córdoba (CPCC) had a higher diversity of orchids than the Paso Coyol Ecological Park (PEPC); however, the diversity found in both sites indicates the potential of urban green areas as refuges for native and endemic orchids. Natural populations of *Platystele stenostachya* are the most numerous at PEPC, while at CPCC *Catasetum integerrimum* is the most abundant species. Phorophyte species found in CPCC and PEPC represented 53 and 90 % of introduced species, respectively. This may be associated with the fact that in the CPCC there is less urbanization. The study of orchid diversity in urban areas helps us to understand how these plants react to environmental disturbances caused by human activity.

## ACKNOWLEDGEMENTS

We thank the Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT) for the scholarship granted to one of the authors for his master's studies at the Colegio de Postgraduados. To Ing. de la Cruz Martínez, for his support in the identification and counting of orchid species.

## REFERENCES

- Acosta-Hernández CF. 2017. Flora arbórea de la universidad de Córdoba, Colombia. *Arquiteturax Visión FUA* 1 (1): 187–197. <https://doi.org/10.29097/26191709.209>
- Alvim FS, Furtado SG, Neto LM. 2020. Diversity of vascular epiphytes in urban green areas of Juiz de Fora, Minas Gerais, Brazil. *Floresta e Ambiente* 27 (2): e20190116. <https://doi.org/10.1590/2179-8087.011619>
- Baltazar-Bernal O, de la Cruz-Martínez VM, Zavala-Ruiz J. 2020. Las orquídeas del Campus Córdoba, su estudio y preservación. *Colegio de Postgraduados: Texcoco, México*. 38 p.
- Carvalho G. 2009. Especies exóticas e invasiones biológicas. *Ciencia Ahora* 23 (12): 15–21.
- Castillo-Pérez LJ, Martínez-Soto D, Maldonado-Miranda JJ, Alonso-Castro AJ, Carranza-Álvarez C. 2018. The endemic orchids of Mexico: a review. *Biología* 74 (1): 1–13. <https://doi.org/10.2478/s11756-018-0147-x>
- Castro SA, Leiva NG, Bolados M, Figueroa JA. 2018. Riqueza y distribución de la flora urbana de Santiago de Chile: una aproximación basada en interpolación IDW. *Caderno de Pesquisa* 30 (1): 41–54. <https://doi.org/10.17058/cp.v30i1.12198>
- CITES (Convention on the International Trade in Endangered Species of Wild Flora and Fauna). 2013. CITES Species. Geneva, Switzerland. <https://cites.org/eng/disc/species.php> (Retrieved: May 2022).
- Córdova-Stroobandt KL. 2013. Caracterización de la biodiversidad urbana en la cuenca central de Cochabamba, Bolivia. *Acta Nova* 6 (1–2): 94–121.
- Coutiño-Cortés AG, Bertolini V, Morales FA, Valle-Mora J, Iracheta-Donjuan L, García-Bautista M, Ruiz-Montoya L. 2018. El uso ornamental de *Guarianthe skinneri* (Orchidaceae), en Chiapas y Guatemala, determina parcialmente su diversidad y estructura genética. *Acta Botánica Mexicana* 124: 35–48. <https://doi.org/10.21829/abm124.2018.1303>
- Cursach JA, Rau JR, Tobar CN, Ojeda JA. 2012. Estado actual del desarrollo de la ecología

- urbana en grandes ciudades del sur de Chile. *Revista de Geografía Norte Grande* 52: 57–70. <https://doi.org/10.4067/s0718-34022012000200004>
- Damon A. 2018. Estrategia para el rescate, conservación y aprovechamiento sustentable de las orquídeas (Orchidaceae) en el sureste de México. *Agro Productividad* 10 (6): 25–30.
- Dávila N, Moura E, Versieux LM, Carvalho FA, Calvente A. 2021. Urban forest fragments as a living laboratory for teaching botany: An example from Federal University of Rio Grande do Norte, Brazil. *Systematic Botany* 46 (1): 6–17. <https://doi.org/10.1600/036364421X16128061189378>
- de Oliveira JAP, Balaban O, Doll CN, Moreno-Peñaranda R, Gasparatos A, Lossifova D, Suwa A. 2011. Cities and biodiversity: Perspectives and governance challenges for implementing the convention on biological diversity (CBD) at the city level. *Biological Conservation* 144 (5): 1302–1313. <https://doi.org/10.1016/j.biocon.2010.12.007>
- DOF (Diario Oficial de la Federación). 2010. NORMA Oficial Mexicana NOM-059-SEMARNAT-2010. Protección ambiental. Especies nativas de México de flora y fauna silvestres, categorías de riesgo y especificaciones para su inclusión, exclusión o cambio. Lista de especies en riesgo. Gobierno de México, Secretaría de Medio Ambiente y Recursos Naturales. Ciudad de México, México. <https://www.dof.gob.mx/normasOficiales/4254/semarnat/semarnat.htm> (Retrieved: May 2022).
- García-Cruz J, Sánchez-Saldaña LM, Jiménez-Machorro R, Solano-Gómez R. 2003. Flora del Bajío y de regiones adyacentes. Orchidaceae, tribu Epidendreae. Herbario AMO: Ciudad de México, México. 178 p.
- Gomes RLP, Campos BC. 2019. Diversidade de epífitas em flora urbana de dois municípios em Minas Gerais, Brasil. *Biológica-Caderno do Curso de Ciências Biológicas* 2 (2): 1–15.
- González-Ball R, Bermúdez-Rojas T, Romero-Vargas M. 2017. Floristic composition and richness of urban domestic gardens in three urban socioeconomic stratifications in the city Heredia, Costa Rica. *Urban Ecosystems* 20 (1): 51–63. <https://doi.org/10.1007/s11252-016-0587-4>
- Hágsater E, Soto MA, Salazar GA, Jiménez-Machorro R, López-Rosas MA, Dressler RL. 2005. Las orquídeas de México. Redacta: Ciudad de México, México. 304 p.
- INEGI (Instituto Nacional de Estadística Geografía e Informática). 2006. Conjunto de datos vectoriales escala 1:1 000 000, precipitación media anual, Estados Unidos Mexicanos [shapefile]. 1:1 000 000. Aguascalientes, México. <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825267544> (Retrieved: May 2022).
- INEGI (Instituto Nacional de Estadística Geografía e Informática). 2007. Conjunto de datos vectoriales escala 1:1 000 000, temperatura media anual, Estados Unidos Mexicanos [shapefile]. 1:1 000 000. Aguascalientes, México. <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825267551> (Retrieved: May 2022).
- INEGI (Instituto Nacional de Estadística Geografía e Informática). 2008. Conjunto de datos vectoriales escala 1:1 000 000, unidades climáticas, Estados Unidos Mexicanos [shapefile]. 1:1 000 000. Aguascalientes, México. <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825267568> (Retrieved: May 2022).
- Izuddin M, Webb EL. 2015. The influence of tree architecture, forest remnants, and dispersal syndrome on roadside epiphyte diversity in a highly urbanized tropical environment. *Biodiversity and Conservation* 24 (8): 2063–2077. <https://doi.org/10.1007/s10531-015-0932-6>
- Izuddin M, Yam TW, Webb EL. 2019. Germination niches and seed persistence of tropical epiphytic orchids in an urban landscape. *Journal of plant research* 132 (3): 383–394. <https://doi.org/10.1007/s10265-019-01110-0>

- Lara B, Rojo J, Blanco JJ, Cardador C, Serrano JI, Soriano D, Pérez-Badia R. 2017. Flora ornamental y potencial alergénico de los espacios verdes urbanos. Comparativa en parques de la ciudad de Toledo. *Revista de Salud Ambiental* 17 (2): 176–186.
- Lowe B, Boudjelas S, de Poorter M. 2000. 100 de las especies exóticas invasoras más dañinas del mundo. Invasive Species Specialist Group: Auckland, Nueva Zelanda. 11 p.
- Lussu M. 2022. Urban orchids: An updated checklist of the orchid flora of Cagliari (Sardinia, Italy). *Biogeographia – The Journal of Integrative Biogeography* 37 (1): a015. <https://doi.org/10.21426/B637156359>
- Newman BJ, Ladd P, Brundrett M, Dixon KW. 2013. Effects of habitat fragmentation on plant reproductive success and population viability at the landscape and habitat scale. *Biological Conservation* 159: 16–23. <https://doi.org/10.1016/j.biocon.2012.10.009>
- Oliván AL, Volponi CR. 2012. Análisis de la vegetación herbácea no gramínea y su relación con el banco de semillas en dos espacios verdes de la ciudad de La Plata, Argentina. *Revista del Museo Argentino de Ciencias Naturales* 14 (2): 253–260.
- Redman CL, Grove JM, Kuby LH. 2004. Integrating social science into the long-term ecological research (LTER) network: social dimensions of ecological change and ecological dimensions of social change. *Ecosystems* 7 (2): 161–171. <https://doi.org/10.1007/s10021-003-0215-z>
- Ruas R de B, Costa LMS, Bered F. 2022. Urbanization driving changes in plant species and communities—A global view. *Global Ecology and Conservation* (38): e02243. <https://doi.org/10.1016/j.gecco.2022.e02243>
- Salazar-Rojas VM, Mata-Rosas M. 2003. Micropropagación y conservación de orquídeas mexicanas en el Jardín Botánico Clavijero. *Lankesteriana* 3 (2): 151–153. <https://doi.org/10.15517/lank.v3i2.23042>
- Shannon CE, Weaver W. 1949. The mathematical theory of communication. University of Illinois Press: Champaign, IL. USA. 125 p.
- Simpson EH. 1945. Measurement of diversity. *Nature* 163 (4148): 688. <https://doi.org/10.1038/163688a0>
- Soto-Arenas M, Hágsater E, Jiménez-Machorro R, Salazar Chávez GA, Flores-González R, Ruiz-Contreras I. 2007. Orquídeas de México. Catálogo digital. Instituto Chinoín: Ciudad de México, México. <https://herbarioamo.org/index.htm> (Retrieved: May 2022).
- Vargas-Garzón B, Molina-Prieto L. 2010. Cinco árboles urbanos que causan daños severos en las ciudades. *Revista nodo* 5 (9): 115–126.
- Villaseñor JL. 2016. Catálogo de las plantas vasculares nativas de México. *Revista Mexicana de Biodiversidad* 87 (3): 559–902. <https://doi.org/10.1016/j.rmb.2016.06.017>

## SPATIAL ANALYSIS OF ANTHRACNOSE IN AVOCADO (*Persea americana* Mill.) IN DONATO GUERRA, MEXICO

Atenas **Tapia-Rodríguez**<sup>1</sup>, José Francisco **Ramírez-Dávila**<sup>2</sup>, Alfredo **Ruiz-Orta**<sup>1</sup>,  
Dulce Karen **Figueroa-Figueroa**<sup>2</sup>, Agustín David **Acosta-Guadarrama**<sup>1</sup>

<sup>1</sup>Universidad Autónoma del Estado de México, Campus Universitario “El Cerrillo”. Facultad de Ciencias Agrícolas, Programa de Maestría y Doctorado en Ciencias Agropecuarias y Recursos Naturales. Carretera Toluca-Ixtlahuaca km 15, El Cerrillo, Piedras Blancas, Toluca, State of Mexico, Mexico. C. P. 50200.

<sup>2</sup>Universidad Autónoma del Estado de México, Campus Universitario “El Cerrillo”. Facultad de Ciencias Agrícolas, Laboratorio de Entomología y Tecnologías Aplicadas a la Agricultura de Precisión. Carretera Toluca-Ixtlahuaca km 15, El Cerrillo, Piedras Blancas, Toluca, State of Mexico, Mexico. C. P. 50200.

\* Author for correspondence: [jframirez@uaemex.mx](mailto:jframirez@uaemex.mx)

### ABSTRACT

Anthracnose is a fungal disease caused by *Colletotrichum* spp. that affects the avocado (*Persea americana* Mill.) crop and causes significant economic losses in the farming sector. To focus control measures, it is important to understand the spatial distribution and the dynamics followed by the disease under field conditions. The use of methods derived from spatial statistics facilitates this task. The aim of this study was to determine the spatial behavior of anthracnose in *Persea americana* Mill. cv. Hass in Donato Guerra, a municipality in the State of Mexico, Mexico, using a geostatistical and spatial analysis by distance indices. Four hundred trees were selected and georeferenced in the municipal area. In order to measure the incidence, 48 fruits were selected from every tree. Using these data, the experimental semivariogram was estimated, and adjustments were made to models that explain the spatial arrangement. Maps were created using ordinary kriging, and the infection area was estimated. The maps generated show the presence of aggregation centers and a spatial distribution mostly fitting Gaussian and exponential models, with ranges fluctuating between 12 and 56 m, indicating spatial association between data. Likewise, the greatest percentage of infected areas was 98 %, while the lowest was 45 %. Geostatistics enables a precise understanding of the distribution patterns of diseases such as anthracnose in avocado-growing areas of the State of Mexico, which facilitates the implementation of integrated management programs with greater effectiveness.

**Keywords:** *Colletotrichum* spp., aggregation, geostatistics, ordinary kriging, semivariogram.

### INTRODUCTION

Mexico ranks first among the 60 commercial avocado (*Persea americana* Mill.) producers in the world, with a contribution of 34.4 % of the total production volume (SIAP, 2022). This economically and nutritionally important crop is affected by phytopathogenic

**Citation:** Tapia-Rodríguez A, Ramírez-Dávila JF, Ruiz-Orta A, Figueroa-Figueroa DK, Acosta-Guadarrama AD. 2024. Análisis espacial de la antracnosis del aguacate (*Persea americana* Mill.) en Donato Guerra, México. *Agrociencia* 58(5): 584-594. <https://doi.org/10.47163/agrociencia.v58i5.2936>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: June 15, 2022.  
Approved: March 03, 2024.  
**Published in Agrociencia:**  
July 16, 2024.

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



agents that limit their commercialization in the international market, forcing farmers to increase their production costs and investments in chemical inputs, causing considerable environmental damage (Lemus *et al.*, 2017).

Donato Guerra is an avocado-producing municipal area in the State of Mexico, with a planted surface of 1531 ha (Figueroa-Figueroa *et al.*, 2020), contributing 13.47 % of the volume produced in the state. One of the phytosanitary problems that harms the crop is anthracnose. It is caused by species of the genus *Colletotrichum* (sexual stage *Glomerella*; Ascomycota, Sordariomycetes, Glomerellaceae), which generate round brown spots and rot the fruit pulp (Ruiz-Campos *et al.*, 2022). This situation generates economic losses for the avocado sector of the state, limiting its commercialization to the domestic market.

The implementation of methodologies such as geostatistics and spatial analysis by distance indices (SADIE) represents a viable alternative towards accurate and timely decision-making regarding crop management since they enable the analysis and interpretation of the spatial relationship of a particular phenomenon. Unlike other statistical methods that characterize the spatial model based on distributions or dispersion indices, geostatistics and SADIE consider the two-dimensional nature of disease distribution through their precise spatial location. Additionally, geostatistics, with the use of a semivariogram and ordinary kriging, enables the representation of the distribution of diseases in the form of maps, whose main function is to show spatial dispersion patterns of diseases in agricultural crops (Ramírez-Dávila *et al.*, 2002; Rivera-Martínez *et al.*, 2022).

There are currently few studies that use methodologies derived from spatial statistics to explain the behavior of fungal diseases in agricultural crops, particularly avocado. The lack of information and management alternatives leads to the incorrect implementation of strategies for the control of the disease in the crop (Cárdenas-Pardo *et al.*, 2017). The aim of this investigation was to understand the spatial distribution of anthracnose in the avocado crop in the municipal area of Donato Guerra with the use of geostatistical analysis and SADIE, assuming that the disease is found in aggregation centers in the area of study.

## MATERIALS AND METHODS

### Area of study

This study was carried out between January and December of 2020 in the municipal area of Donato Guerra, located in the center of the State of Mexico (19° 18' 29.87" N, 100° 8' 31.19" W) (INEGI, 2022), with an average altitude of 2200 m, a mean annual temperature of 19.2 °C, and an average rainfall of 1000 mm. The area of study is one of the main avocado-producing areas in the region (Lara-Díaz *et al.*, 2019).

### Sampling method

Four hundred avocado trees were selected, georeferenced, and marked, considering one tree as a sampling unit and covering the entire surface of the municipal area with the quadrant method. The trees were verified to be 10 years old, and agronomic management was carried out in a similar manner. Every sampled tree was georeferenced using a DGPS (PRO-XR Trimble; CO, USA) to establish its geographic coordinates. Likewise, moisture, rainfall, and temperature data were taken from the Donato Guerra weather station (CONAGUA, 2022).

Each tree was classified into three strata: high, medium, and low, and four branches were chosen from each stratum, one for each cardinal point. To determine the incidence of anthracnose, 48 fruits with symptoms were selected from each branch, and samples were collected for a simultaneous study to identify and confirm the presence of *Colletotrichum gloeosporioides*. Sampling was performed biweekly between January and December 2020.

### Spatial Analysis by Distance Indices (SADIE)

Using this analysis, the indices were determined based on distances for regularity ( $I_a$ ) and clustering ( $J_a$ ). Indices were estimated with the data gathered from a predesigned grid composed of sampling units that are assumed to be an individual counting system. A sample is said to be aggregated if  $I_a > 1$ , spatially random if  $I_a = 1$ , and regular if  $I_a < 1$ . A total of 2000 randomizations are sufficient to derive the values of the corresponding indices. The term  $C$  denotes the distance for clustering, that is, the minimum total distance value that sample individuals must move to gather in a unit. This value is nearer to the distance for regularity ( $D$ ), using a simple direct search on all the sampling units. The sampling unit with the minimum value is referred to as the "cluster center" of the clustering. Random permutations of the observed counts result in a ratio known as  $Q_a$  (clustering probability), with a clustering distance equal to or smaller than the observed value  $C$ .

As in the case of index  $I_a$ ,  $J_a$  values  $> 1$  usually indicate an aggregated sample,  $J_a = 1$  represents spatially random data, and  $J_a < 1$  represents regular samples. In this way, the values of index  $J_a$  are useful to corroborate the results obtained using index  $I_a$ . Furthermore, this index is used to distinguish between spatial patterns with only one important cluster whose values are significantly greater than the unit and those with two or more clusters whose values are not significantly different from or even lower than the unit. The unit's probability ( $Q_a$ ) is used to determine its significance. Because the values of  $I_a$  and  $J_a$  for random counts are uncorrelated, 2000 randomizations can be used in the software that calculates their respective values. In this work, the values and probabilities of both indices were determined using AEID 1.22. (Perry and Klukowsky, 1997).

### Geostatistical analysis

Using the anthracnose incidence data collected in the area of study, a statistical estimation was performed to determine its normality. Subsequently, to obtain the

experimental semivariogram, the Variowin 2.2 program (Spring Verlag; NY, USA) was used. The experimental semivariograms were fitted to the theoretical semivariograms, obtaining the structural parameters of the model to be validated: effect, plateau, and range effects. These indicators were adjusted in a trial-and-error procedure until suitable cross-validation statistics were obtained: mean squared error, mean estimation error, and dimensionless mean squared error.

#### **Level of spatial dependence**

The level of spatial dependence was determined by dividing the nugget effect by the plateau. The result of this operation is expressed as a percentage, using the following criteria as an explanation: a result below 25 % indicates a high level of spatial dependence; values between 26 and 75 % are reported as moderate; and finally, a value above 76 % indicates a low level of spatial dependence for the data of the phenomenon under study (Lara-Díaz *et al.*, 2020; Rivera-Martínez *et al.*, 2022; Satish *et al.*, 2023).

#### **Infected surface maps**

To represent the surface infected with anthracnose, the ordinary kriging method was used, enabling the estimation of values related to points that were not sampled, thus reducing the sampling error and ensuring that the scale used was correct (Samper-Calvete and Carrera, 1996). With these estimations, maps were generated for every sampling day using the Surfer 16 program (Surface Mapping System, Golden Software Inc.; CO, USA).

## **RESULTS AND DISCUSSION**

#### **Spatial Analysis by Distance Indices**

For the  $I_a$  index, the value was clearly located between 1.4 and 1.78. In all cases, the  $I_a$  index was significantly higher than 1 (Table 1), which indicates an aggregate spatial distribution of anthracnose inside the sampling zone. In terms of the  $J_a$  index, the lowest value was 1.11 and the highest was 1.26. In all cases, for sampling dates, the  $J_a$  index was higher than 1, but not significant in any case. However, this emphasizes the aggregation detected by the  $I_a$  index. Additionally, the  $J_a$  index indicates the number of aggregation centers present in each sample; since these values were not significantly different from the unit, the result was that anthracnose is distributed in the sampling area in more than one aggregation center. This type of distribution has been found in works such as the one by Perry and Klukowsky (1997) on aphid eggs, or Winder *et al.* (1999) on the populations of *Sitobion avenae* eggs, and Tapia-Rodríguez *et al.* (2021) on the avocado crop.

The  $J_a$  index results were not significantly higher than the unit, indicating that anthracnose is distributed across multiple aggregation foci. This coincides with Korie *et al.* (1998), who worked with beetles on winter oats in the United Kingdom,

**Table 1.** Value of the indices of regularity (Ia) and clustering (Ja) and their respective probabilities (Pa and Qa) on the incidence of anthracnose in *Persea americana* Mill. in the municipal area of Donato Guerra, State of Mexico, Mexico.

Month	Sampling	Ia	Pa	Ja	Qa
January	1	1.41	0.011 s	1.15	0.246 ns
	2	1.65	0.014 s	1.11	0.230 ns
February	1	1.47	0.008 s	1.20	0.282 ns
	2	1.44	0.010 s	1.22	0.269 ns
March	1	1.78	0.012 s	1.17	0.301 ns
	2	1.61	0.009 s	1.26	0.325 ns
April	1	1.57	0.014 s	1.16	0.328 ns
	2	1.50	0.009 s	1.19	0.255 ns
May	1	1.68	0.008 s	1.24	0.239 ns
	2	1.63	0.016 s	1.25	0.279 ns
June	1	1.56	0.012 s	1.22	0.244 ns
	2	1.71	0.015 s	1.21	0.299 ns
July	1	1.43	0.013 s	1.13	0.275 ns
	2	1.52	0.010 s	1.24	0.307 ns
August	1	1.66	0.012 s	1.20	0.315 ns
	2	1.74	0.013 s	1.16	0.266 ns
September	1	1.70	0.007 s	1.27	0.263 ns
	2	1.40	0.012 s	1.17	0.320 ns
October	1	1.76	0.011s	1.19	0.262 ns
	2	1.55	0.008 s	1.12	0.322 ns
November	1	1.64	0.015 s	1.13	0.251 ns
	2	1.48	0.015 s	1.18	0.286 ns
December	1	1.59	0.013 s	1.23	0.311 ns
	2	1.72	0.011 s	1.14	0.290 ns

ns: not significant; s: significant.

and Ramírez-Dávila *et al.* (2014), who studied the spatial distribution of *Sporisorium reilianum* in maize. Rivera-Martínez *et al.* (2020) performed a study on the spatial behavior of *Bactericera cockerelli* nymphs on husk tomato, in which the Ja values established the number of aggregation centers. In that study, the Ja value was not significantly greater than 1, which helped establish that the spatial distribution of the disease was concentrated in different aggregation centers.

#### Geostatistical analysis

Twenty-four semivariograms were estimated for the incidence of anthracnosis in avocado fruits; six of them were fitted to spherical models, nine to Gaussian models, and nine to exponential models. This helped to properly characterize spatial continuity, thus coinciding with reports by Lara-Díaz *et al.* (2020) and Cárdenas-Pardo *et al.* (2017),

who used semivariograms to analyze disease incidence in cocoa genotypes and found them to be an accurate tool for detecting spatial continuity.

The models of the semivariogram were submitted to the cross-validation process, in which the values reflected optimum ranges to continue with the geostatistical process (Isaaks and Srivastava, 1989; Harding and Deutsch, 2021). The cross-validation process has been applied in several studies in the State of Mexico to verify the accuracy of the model to which the distribution has been fitted (Lara-Díaz *et al.*, 2018; Tapia-Rodríguez *et al.*, 2020).

The nugget effect was equal to zero on all the sampling dates; therefore, the sampling error was minimal and the scale used was adequate (Table 2). The entire variation in the distribution of anthracnose is due to the spatial structure established in the corresponding semivariograms for each sampling performed, coinciding with the studies by Lara-Díaz *et al.* (2020) and dos Santos *et al.* (2023). For all sampling dates, a high level of spatial dependence was found, indicating a high spatial relationship between every sampling point.

**Table 2.** Parameters of the theoretical models adjusted to the anthracnose semivariograms, by sampling date, in Donato Guerra, State of Mexico, Mexico.

Sampling	Sample mean	Sample variance	Model	Nugget	Range	Plateau	Nugget/plateau (%)	Spatial dependence
January 1	6.05	12.46	Spherical	0	20.8	10.01	0	High
January 2	2.22	2.92	Gaussian	0	26.6	3.75	0	High
February 1	2.025	1.66	Gaussian	0	22.4	1.37	0	High
February 2	1.94	1.46	Spherical	0	22.4	1.44	0	High
March 1	1.47	1.25	Gaussian	0	17.6	1.14	0	High
March 2	2.92	1.64	Exponential	0	22.4	1.42	0	High
April 1	13.65	31.78	Spherical	0	28.16	16.79	0	High
April 2	3.47	2.41	Gaussian	0	20.3	2.28	0	High
May 1	3.91	2.78	Exponential	0	21.8	2.52	0	High
May 2	4.27	6.59	Gaussian	0	19.6	4.42	0	High
June 1	4.23	3.97	Gaussian	0	24.6	2.31	0	High
June 2	4.97	5.15	Exponential	0	22.8	3.64	0	High
July 1	6.55	8.14	Exponential	0	26.2	6.63	0	High
July 2	7.65	7.18	Gaussian	0	22.2	4.63	0	High
August 1	9.04	5.08	Gaussian	0	16.6	5.26	0	High
August 2	6.05	12.46	Spherical	0	21.8	10.6	0	High
September 1	5.57	9.94	Exponential	0	20.8	8.1	0	High
September 2	5.94	11.96	Exponential	0	21.9	9.12	0	High
October 1	5.86	12.36	Exponential	0	28	12.30	0	High
October 2	5.89	11.55	Gaussian	0	17.6	10.8	0	High
November 1	5.51	11.98	Spherical	0	20.8	9.56	0	High
November 2	6.02	11.39	Exponential	0	22.3	8.86	0	High
December 1	6.49	10.97	Exponential	0	19.2	10.27	0	High
December 2	5.85	13.51	Spherical	0	22.4	11.6	0	High

The spatial association range remained between 17.6 and 28.16 m, indicating the distance at which the data are spatially related. The range values found indicate that the validity of the fitted models extends to nearby distances in explaining the anthracnose aggregation phenomenon. The plateau values ranged between 1.37 and 12.3, indicating the type of aggregation present.

The maximum number of diseased fruits discovered between samplings was 12 per tree, primarily in April, June, July, and August. This is due to the presence of constant and abundant rainfall in the production area, while the decrease in temperature had an influence in January, February, October, November, and December.

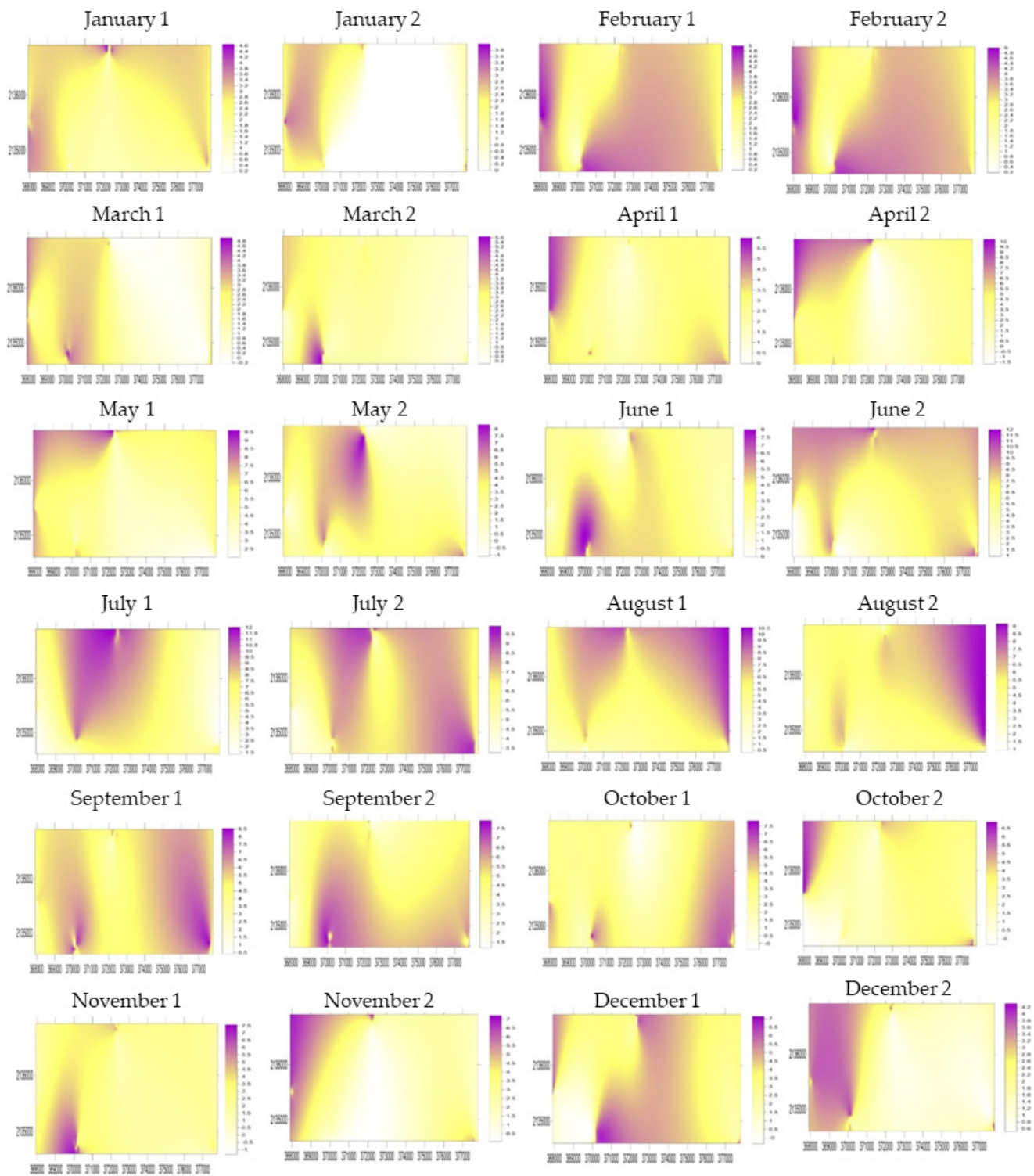
### Infected surface maps

The infected surface was calculated for the 24 sampling dates. The infected surface in the area of study was greater than 40 %. In both samplings, this value reached 98 %, as opposed to 45 % as the lowest value. Likewise, 24 incidence maps were created (Figure 1), which correspond to the 24 samplings conducted from January to December 2020 on a biweekly basis. These maps show aggregation centers graphically and help interpret the behavior of the disease within the study area. In all infection maps obtained, at least one aggregation center was observed, with an average of three well-defined aggregation centers, which remained present throughout the twelve months of sampling and can be seen in the upper, central, and lower right parts of each map (Figure 1).

The infection foci found in each map matched the location of avocado trees that displayed symptoms of the disease. The ordinary kriging interpolation technique has been used previously in studies related to diseases, such as those conducted by Cárdenas-Pardo *et al.* (2017) in cacao, Quiñones-Valdez *et al.* (2015) in gladiolus, and Rivera-Martínez *et al.* (2022) for the analysis of pests in avocado crops in the State of Mexico, verifying the effectiveness of kriging.

This spatial arrangement of aggregation centers indicates that the disease behaved in a stable manner, advancing from the top and bottom, with another focus in the center of the map, similar to findings by Alves *et al.* (2006) and Huded *et al.* (2022). In these studies, diseases such as anthracnose display an initial focus and then generate secondary foci, allowing the spread of the disease throughout the sampled area. Quiñones-Valdez *et al.* (2015) and Ruiz-Orta *et al.* (2023) suggest that control measures must be directed towards specific sites where the disease shows high infection rates.

It is evident that the application of geostatistical techniques helped establish the distribution and intensity of the harmful agents based on all the available spatial information used to create the maps and obtain unbiased estimates of unsampled points. These maps are highly useful since they help establish more effective control tactics. On the other hand, the characteristics related to the productive systems, such as crop age and the number of fruits selected per tree, explain the appearance of anthracnose, since older trees have been observed to be more susceptible to the disease in comparison to younger trees.



**Figure 1.** Biweekly maps \* of the surface infected by anthracnose in *Persea americana* Mill. between January and December 2020 in Donato Guerra, State of Mexico, Mexico. \*1: first fortnight of the month; 2: second fortnight of the month.

Agroclimatic conditions, such as relative humidity and rainfall in Donato Guerra, may have had a significant influence on the dynamics of the dispersal of the disease, particularly between April and September, where the presence of infection foci can be observed. Another important factor in the dissemination and possible progress of anthracnose were the management practices that the farmers used on the trees. The use of contaminated tools to prune and harvest fruits favors the transportation of the inoculum to healthy plants. During the samplings, few farmers were observed to remove the branches and leaves from pruning, which is why *C. gloeosporioides* remained in the orchards.

### CONCLUSIONS

Anthracnose in the municipal area of Donato Guerra displayed an aggregate spatial distribution, forming infection foci that remained stable during the entire sampling period. The aggregate spatial distribution of the disease in *Persea americana* Mill. obtained with the use of spatial analysis by distance indices was verified with geostatistical analysis and the maps created using kriging. The creation of maps of the infested surface helped detect areas with a high percentage of infection, which will help propose alternatives directed at a timely, efficient, and sustainable phytosanitary management of the avocado crop in Donato Guerra.

### ACKNOWLEDGEMENTS

To the National Science and Technology Council for the scholarship granted for postgraduate studies. To the avocado farmers in the municipal area of Donato Guerra.

### REFERENCES

- Alves MC, Pozza EA, Machado JC, Araújo DV, Talamini V, Oliveira MS. 2006. Geoestatística como metodologia para estudar a dinâmica espaço-temporal de doenças associadas a *Colletotrichum* spp. transmitidos por sementes. *Fitopatologia Brasileira* 31 (1): 557–563. <https://doi.org/10.1590/s0100-41582006000600004>
- Cárdenas-Pardo NJ, Darghan A, Sosa-Rico MD, Rodríguez A. 2017. Análisis espacial de la incidencia de enfermedades en diferentes genotipos de cacao (*Theobroma cacao* L.) en El Yopal (Casanare), Colombia. *Acta Biológica Colombiana* 22 (2): 209–220.
- CONAGUA (Comisión Nacional del Agua). 2022. Red de estaciones climatológicas. Gobierno de México. Secretaría del Medio Ambiente y Recursos Naturales. Comisión Nacional del Agua. Servicio Meteorológico Nacional. Ciudad de México, México. <https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/informacion-estadistica-climatologica> (Retrieved: March 2024).
- dos Santos MP, de Mates EC, Santos Neto B de M, Cardoso ACP, Leite SA, Moreira AA, Albuquerque EVS, Fernandes DRR, Hilliou F, de Carvalho GA, Castellani MA. 2023. Morphometric variation and fluctuating asymmetry in populations of *Closterocerus coffeellae*

- (Ihering) (Hymenoptera: Eulophidae) in different management and landscape of coffee agroecosystems. <https://doi.org/10.2139/ssrn.4665544>
- Figueroa-Figueroa DK, Ramírez-Dávila JF, Antonio-Némiga X, González-Huerta A. 2020. Cartografía del aguacate en el sur del Estado de México mediante tratamiento digital de imágenes sentinel-2. *Revista Mexicana de Ciencias Agrícolas* 11 (4): 865–879. <https://doi.org/10.29312/remexca.v11i4.2173>
- Harding B, Deutsch CV. 2021. Trend modeling and modeling with a trend. In Deutsch JL. (ed.), *Geostatistics Lessons. Resource Modeling Solutions*: Calgary, Canada. 14 p.
- Huded S, Pramesh D, Chittaragi A, Sridhara S, Chidanandappa E, Prasannakumar MK, Shamshiri RR. 2022. Spatial distribution patterns for identifying risk areas associated with false smut disease of rice in Southern India. *Agronomy* 12 (12): 2947. <https://doi.org/10.3390/agronomy12122947>
- INEGI (Instituto Nacional de Estadística, Geografía e Informática). 2022. Anuario de estadísticas por entidad federativa. Ciudad de México, México. <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=889463901846> (Retrieved: March 2024).
- Isaaks EH, Srivastava RM. 1989. An introduction to applied geostatistics. Oxford University Press: New York, NY, USA, pp: 35–38.
- Korie S, Clark SJ, Perry JN, Muggleston MA, Bartlett PW, Marshall EJP, Mann JA. 1998. Rejoinder analyzing maps of dispersal around a single focus. *Environmental and Ecological Statistics* 5 (4): 349–351. <https://doi.org/10.1023/a:1009603804998>
- Lara-Díaz AV, Ramírez-Dávila JF, Maldonado-Zamora FI, Figueroa-Figueroa DK, Acosta-Guadarrama AD, Rivera-Martínez R, Némiga XA. 2018. Simulación espacial de *Claviceps gigantea* (Fuentes, de la Isla, Ullstrup y Rodríguez) en el Estado de México. *Revista Mexicana de Ciencias Agrícolas* 9 (1): 95–109. <https://doi.org/10.29312/remexca.v9i1.850>
- Lara-Díaz AV, Ramírez-Dávila JF, Maldonado-Zamora FI, Rivera-Martínez R, Acosta-Guadarrama AD, Lara-Vázquez F. 2020. Modelización espacial de las poblaciones de *Oligonychus perseae* (Tuttle, Baker y Abatiello, 1976) en el Estado de México. *Revista Fitotecnia Mexicana* 43 (4): 411–419.
- Lara-Díaz AV, Ramírez-Dávila JF, Rubí-Arriaga M, Campos-Alanis J, Maldonado-Zamora FI, Rivera-Martínez R, Acosta-Guadarrama AD. 2019. Modelización espacial de *Oligonychus perseae* (Tuttle, Baker y Abatiello) mediante técnicas geoestadísticas. *Revista Mexicana de Ciencias Agrícolas* 10 (6): 1405–1416. <https://doi.org/10.29312/remexca.v10i6.1951>
- Lemus C, Bugarín J, Grageola F, Rodríguez JG, Mejía K, Valdivia R. 2017. Características químicas de la pasta de aguacate Hass fruto completo (*Persea americana* Mill.) mexicano de Nayarit destinado a la alimentación animal. *Revista Computadorizada de Producción Porcina* 24 (2): 212–218.
- Perry N, Klukowsky Z. 1997. Spatial distributions of counts at the edges of sample areas. In VI Conference of the Biometric Society. International Biometric Society: Cordoba, Spain, pp: 103–108.
- Quiñones-Valdez R, Sánchez-Pale JR, Pedraza-Esquivel AK, Castañeda-Vildozola A, Gutierrez-Ibañez AT, Ramírez-Dávila JF. 2015. Análisis espacial de *Thrips* spp. (Thysanoptera) en el cultivo de gladiolo en la región sureste del Estado de México, México. *Southwestern Entomologist* 40 (2): 397–408. <https://doi.org/10.3958/059.040.0213>
- Ramírez-Dávila J, González-Andújar JL, Ocete R, Martínez LM. 2002. Descripción geoestadística de la distribución espacial de los huevos del mosquito verde *Jacobiasca lybica* (Bergenin

- & Zanon) (Homoptera: Cicadellidae) en viñedo: modelización y mapeo. *Boletín Sanidad Vegetal de Plagas* 28 (1): 87–95.
- Ramírez-Dávila JF, Sánchez-Pale JR, Figueroa-Figueroa DK, de León C. 2014. Asociación espacial de largo plazo de *Sporisorium reilianum* en el cultivo de maíz. *Revista Mexicana de Micología* 40 (1): 37–45.
- Rivera-Martínez R, Ramírez-Dávila JF, Martínez-Quiroz M, González-Huerta A. 2020. Modelización espacial de ninfas de *Bactericera cockerelli* Sulc. en tomate de cáscara (*Physalis ixocarpa* Brot.) por medio de técnicas geoestadísticas. *Biotecnia* 22 (1): 142–152. <https://doi.org/10.18633/biotecnia.v22i1.1162>
- Rivera-Martínez R, Ramírez-Dávila JF, Tapia-Rodríguez A, Figueroa-Figueroa DK, Acosta-Guadarrama AD, Serrato-Cuevas R. 2022. Comportamiento espacial del barrenador de la rama en aguacate utilizando el método del SADIE en el Estado de México. *Revista Mexicana de Ciencias Agrícolas* 13 (2): 247–259. <https://doi.org/10.29312/remexca.v13i2.2728>
- Ruiz-Campos C, Umaña-Rojas G, Gómez-Alpizar L. 2022. Identificación multilocus de especies de *Colletotrichum* asociadas a la antracnosis de papaya. *Agronomía Mesoamericana* 33 (1): 45495. <https://doi.org/10.15517/am.v33i1.45495>
- Ruiz-Orta A, Tapia-Rodríguez A, Figueroa-Figueroa DK, Ramírez-Dávila JF. 2023. Analysis of the spatial association of fumagina (*Capnodium* spp.) and green scale (*Coccus viridis*) in coffee in Sultepec, Mexico. *Agrociencia* 57 (7). <https://doi.org/10.47163/agrociencia.v57i7.2945>
- Samper-Calvete FJ, Carrera J. 1996. *Geoestadística: aplicaciones a la hidrología subterránea* (Segunda edición). Centro Internacional de Métodos en Ingeniería: Barcelona, España. 484 p.
- Satish Y, Shekhar S, Rathod ASS, Chouksey N. 2023. Spatial variability of soil micronutrients in Raichur district of Karnataka. *International Journal of Statistics and Applied Mathematics* 8 (4): 560–567.
- SIAP (Servicio de Información Agroalimentaria y Pesquera). 2022. Sistema de información agroalimentaria de consulta nueva generación (SIACON). Gobierno de México. Sistema de información agroalimentaria de consulta nueva generación (SIACON NG). Ciudad de México, México. <https://www.gob.mx/siap/documentos/siacon-ng-161430> (Retrieved: March 2024).
- Tapia-Rodríguez A, Ramírez-Dávila JF, Aquino-Martínez JG, Arriaga MR, Ruiz-Orta A. 2021. Determination of the spatial behavior of anthracnose in avocado cultivation using spatial statistics. *Investigación Agraria* 23 (2): 63–72. <https://doi.org/10.18004/investig.agrar.2021.diciembre.2302697>
- Tapia-Rodríguez A, Ramírez-Dávila JF, Figueroa-Figueroa DK, Salgado-Siclán ML, Serrato-Cuevas R. 2020. Análisis espacial de antracnosis en el cultivo de aguacate en el Estado de México. *Revista Mexicana de Fitopatología* 38 (1): 132–145. <https://doi.org/10.18781/r.mex.fit.1911-1>
- Winder L, Perry JN, Holland JM. 1999. The spatial and temporal distribution of the grain aphid *Sitobion avenae* in winter wheat. *Entomologia Experimentalis et Applicata* 93 (3): 275–288. <https://doi.org/10.1046/j.1570-7458.1999.00588.x>

## PRODUCTION AND EXPORT OF BERRIES IN MEXICO'S AGRICULTURAL DEVELOPMENT: A STUDY OF COMPETITIVE ADVANTAGE

Jesús Ernesto Rocha-Ibarra<sup>1</sup>, Ana Isabel Mireles-Arriaga<sup>2</sup>,  
Jorge Eric Ruiz-Nieto<sup>2</sup>, Griselda Maki-Díaz<sup>1\*</sup>

<sup>1</sup>Universidad de Guanajuato, Campus Irapuato-Salamanca. División de Ingenierías, Departamento de Arte y Empresa. Carretera Salamanca-Valle de Santiago km 3.5 + 1.8, Comunidad de Palo Blanco, Salamanca, Guanajuato, Mexico. C. P. 36885.

<sup>2</sup>Universidad de Guanajuato, Campus Irapuato-Salamanca. División de Ciencias de la Vida, Departamento de Agronomía. Carretera Irapuato-Silao km 9, ex Hacienda El Copal, Irapuato, Guanajuato, Mexico. C. P. 36500.

\* Author for correspondence: g.maki@ugto.mx

### ABSTRACT

The production and marketing of fruits and vegetables is one of the most important economic activities for agricultural development in Mexico. The group of berries, including raspberry (*Rubus idaeus* L.), strawberry (*Fragaria* spp.), blackberry (*Rubus ulmifolius* Schott), and blueberry (*Vaccinium* spp.), has positioned Mexico among the main exporting countries of these products, where the value of exports has maintained a growing trend in recent decades. The index of revealed comparative advantage (VCR) identifies countries that have a competitive advantage over others in a given product and compares competitive trends in the same market. The objective of this study was to determine Mexico's competitive advantage in the production and export of berries under the hypothesis that there is a positive index of revealed comparative advantage in the export of berries. The VCR and the trade openness index were computed by examining the historical trends in berry production and its involvement in both domestic and international markets. The value and volume of berry production have increased significantly since 2010, which places Mexico among the three main producing countries. It is notable that the trade openness of the Mexican agricultural sector has increased during the period 2001–2019. In addition, a comparative advantage has been demonstrated in strawberry exports, which positions Mexico as one of the main exporters of this product and represents an important competitive position in world trade since berry exports exceed imported volumes. Therefore, Mexico has a positive and growing comparative advantage, which makes it competitive with the leading countries in the production and export of berries.

**Keywords:** competitiveness, strawberry, raspberry, blackberry, trade openness.

### INTRODUCTION

Mexico is one of the main producers and exporters of fruit and vegetable crops in the world (FAO, 2021). The fruit and vegetable sector is one of the most profitable activities

**Citation:** Rocha-Ibarra JE, Mireles-Arriaga AI, Ruiz-Nieto JE, Maki-Díaz G. 2024. Production and export of berries in Mexico's agricultural development: a study of competitive advantage. *Agrociencia* 58(5): 595-608. <https://doi.org/10.47163/agrociencia.v58i5.2836>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: August 09, 2022.  
Approved: February 27, 2024.  
**Published in Agrociencia:**  
July 05, 2024.

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



(Ayala-Garay *et al.*, 2012), with a 56 % increase between 1990 and 2003 (Aksoy, 2005). The Mexican countryside is in a transformation stage, according to current trends, in agricultural production in some states in central Mexico, where traditional crops such as corn, wheat, or sorghum have been replaced by horticultural crops adapted to the local soil and climate (Bustillos-Durán, 2015; Martínez-Borrego, 2016). Other factors, such as changes in prices and consumption habits, also determine the type of crop to produce (Cruz-Delgado *et al.*, 2013).

The group of crops known as “berries” has distinguished itself for its commercial worth. In the present study, raspberries (*Rubus idaeus* L.), strawberries (*Fragaria* spp.), blackberries (*Rubus ulmifolius* Schott), and blueberries or mulberries (*Vaccinium* spp.) were considered. Since 2016, these crops have presented a considerable production increase (FAO, 2021; SIAP, 2021). The value of Mexican berry exports increased from \$64 815 thousand USD in 2001 to \$1 048.256 million USD in 2020 (FAO, 2021; INTRACEN, 2021). Mexico is one of the main exporters of berries. In 2020, the volume of strawberry exports was 125 929 Mg, while that of the group of raspberries, blackberries, and mulberries was 47 942 Mg (INTRACEN, 2021).

The main producing states are Michoacán, Baja California, Jalisco, and Guanajuato, which contribute more than 90 % of national production (SIAP, 2021). In Mexico, in 2020, the total area planted with berries was 35 784 ha, with a production value of \$41 520.358 million MXN (SIAP, 2020; 2021). Currently, consumers have expanded their acceptance of berries for their various nutraceutical qualities (Beattie *et al.*, 2005; González-de Mejía and Johnson, 2017; Sangiovanni *et al.*, 2017; Foito *et al.*, 2018), which can be related to the increase in national and international demand.

### Competitiveness of agricultural crops

Competitiveness is defined as the ability of an organization to achieve an advantage in order to attain and maintain a position in the environment. Companies generate competitive advantages from their skills, resources, and knowledge about themselves and their competitors, making it possible to obtain superior performance. This can be achieved in two ways: by creating value at a lower cost than the competition or by generating differentiation at a higher price (Porter, 2011). In contrast, comparative advantage is an indicator of the terms of trade between two or more countries or a country and the rest of the world (Ayvar-Campos *et al.*, 2018).

Mexico is one of the most competitive countries in the agricultural sector. The production and export of fruits and vegetables represent one of the most profitable activities in the Mexican countryside (FAO, 2021; SIAP, 2021). In 2020, Mexico ranked sixth (23 678 584 Mg) and ninth (15 226 085 Mg) in fruit and vegetable production worldwide, respectively (FAO, 2021), and the area devoted to fruit and vegetable crops was 2 188 848 ha (FAO, 2021), which represented approximately 2.8 % of the national agricultural area. The value of fruit and vegetable exports for Mexico in the same year was \$12 431.748 million USD, which placed it sixth among the main exporting countries of this group of products, after the USA (FAO, 2021).

Berries' participation in the national production of fruits during 2020 was the following: blueberry 0.2 %, raspberry 0.5 %, strawberry 3.6 %, and blackberry 1.3 % (SIAP, 2020). In world production, Mexico ranked sixth in blueberry (48 999 Mg), second in raspberry (128 848 Mg), third in strawberry (861 337 Mg), and was the world's leading producer of blackberry (298 024 Mg) (INTRACEN, 2021; FAO, 2021). Per capita consumption of berries in Mexico in the same year was: blueberry 0.1 kg, raspberry 0.3 kg, strawberry 4.7 kg, and blackberry 1.8 kg (SIAP, 2021).

### International trade of berries

The positioning of berries in the agri-food market is mainly due to the fact that producers have been able to take advantage of opportunities. Appropriate technologies have been included in their production processes to raise efficiency, such as the production of varieties with optimal development characteristics, the implementation of production systems under cover, and technified irrigation, in addition to traditional cultural work such as manual harvesting to ensure the quality of the fruits (Housni *et al.*, 2018).

The economic importance of berries is reflected in the increase in world production. Between 2005 and 2019, world production of strawberries, raspberries, and blueberries increased from 6 626 284 to 10 530 849 Mg. In Mexico, in 2005, the value of strawberry production was \$2 248.819 million MXN, which represented 1.1 % of the total value of agricultural production in Mexico. In 2020, the value of production was \$41 520.358 million MXN, representing 6.1 % of the total value of agricultural production in Mexico (SIAP, 2020; 2021). Berries ranked third in agri-food products exported by Mexico, with a value of \$2615 million USD (SIAP, 2021).

In regard to total world production, in 2019, China, the USA and Mexico were the leaders in strawberry production (42 %); Russia, Mexico, and Serbia in raspberry production (51 %); and the USA, Canada, and Peru (76 %) in blueberry production, in which Mexico ranked fifth (48 999 Mg). Mexico is the second-largest raspberry producer in the world (FAO, 2021; INTRACEN, 2021). Therefore, the objective of this research was to determine Mexico's competitive advantage in the production and export of strawberries, based on the hypothesis that this country has a positive index of comparative advantage revealed in the export of Mexican berries.

### MATERIALS AND METHODS

To determine Mexico's competitive advantage in the production and export of berries (strawberries, raspberries, blackberries, and blueberries), the historical behavior of berry production and its participation in the national and international markets were analyzed. A historical series from 2001 to 2019 was generated by compiling data obtained from various official sources (SIAP 2020, 2021; SAGARPA, 2017; FAO, 2021; INTRACEN, 2021) on the production and marketing of berries in Mexico and in the main producing and exporting countries.

Similarly, the revealed comparative advantage index (VCR) proposed by Vollrath (1991) was used, which analyzes the comparative advantages or disadvantages of a country's trade with its trading partners. This indicator identifies countries that have a competitive advantage over others in a given product and compares trends in competitiveness among competitors in the same market. It is expressed as follows:

$$VCR_{ai} = VCE_{ai} - VCI_{ai}$$

$$VCE = \ln \left[ \frac{X_{ai}}{X_{in}} \frac{X_{ra}}{X_{rn}} \right]$$

$$VCI = \ln \left[ \frac{M_{ai}}{M_{in}} \frac{M_{ra}}{M_{rn}} \right]$$

where  $VCE$  is the revealed comparative advantage of exports,  $VCI$  is the revealed comparative advantage of imports,  $r$  indicates the world value minus the value of the country under analysis (country  $i$ ),  $n$  is the trade value of all goods minus the value of a good,  $a$  is the value of the good under study,  $i$  is the country for which the analysis is being conducted,  $X$  are exports, and  $M$  are imports.

The calculation of the trade openness index (AC) requires the values of total exports, total imports, and agricultural gross domestic product (GDP). It is obtained using the following formula:

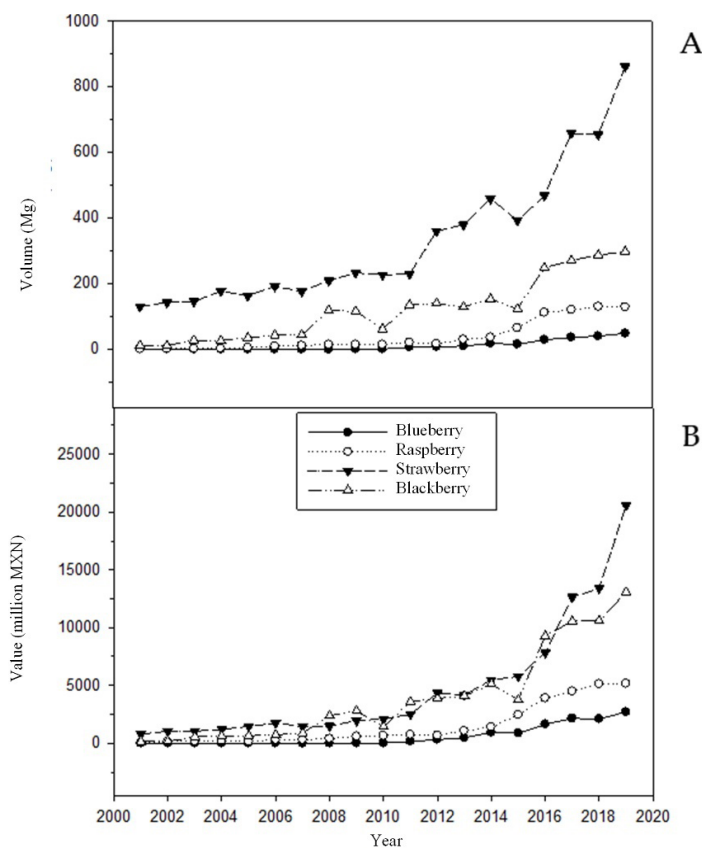
$$AC = \frac{\text{Value of agricultural exports} + \text{Value of agricultural imports}}{\text{Gross domestic product from agriculture}} * 100$$

## RESULTS AND DISCUSSION

### Domestic production of berries

The value and volume of production of the group of berries analyzed had a significant increase from 2010 onwards (Figure 1), where strawberry and blackberry crops stood out considerably. By 2019, strawberry production was 861 336 Mg, with a value of \$20 584.207 million MXN; blackberry production was 298 024 Mg, with a value of \$13 068.299 million MXN (FAO, 2021).

Michoacán is the largest blackberry producer in Mexico, where 66 % of the domestic production of the group of berries under study is concentrated (Table 1). In that state, blackberry became a strategic crop and managed to position itself for its profitability



**Figure 1.** Berry production in Mexico from 2001 to 2020 (Own design with data from INTRACEN, 2021). A: production volume; B: production value.

and potential in the export market (Coronado-García *et al.*, 2014; Muratalla-Lúa *et al.*, 2018). This berry is recognized for its antioxidant properties, flavor, and various forms of marketing and consumption (Oszmiański *et al.*, 2015; Souza *et al.*, 2015). Regarding strawberries, 52 % of production is destined for the international market, while in the

**Table 1.** Value (millions of MXN) and volume of berry production by state in Mexico.

State	Volume 2018 (Mg)	Volume 2019 (Mg)	Volume variation 2018–2019 (%)	Value 2019
Michoacán	760 428	883 762	1.2	27 207.176
Baja California	134 577	216 829	1.6	9 456.085
Jalisco	120 834	129 016	1.1	3 308.293
Guanajuato	67 693	82 034	1.2	939.869
Rest of the country	27 659	25 566	0.9	608.934

Source: SIAP, 2020; 2021.

domestic market, 85 % of production is destined for the agroindustry for the production of jam (SAGARPA, 2017). Programs focused on the promotion of agriculture as well as efficiency in the application of production methods have contributed to the increase in Mexican strawberry production (Ramírez-Padrón *et al.*, 2016).

Berry production in Mexico is concentrated in Michoacán (66 %), Baja California (16 %), Jalisco (10 %), and Guanajuato (6 %) (Table 1). Michoacán is the most important state in strawberry and raspberry production, where the establishment of marketing companies has increased, as well as the area used for cultivation, labor, and the opening of new markets (Sánchez-Rodríguez, 2008). The case of Guanajuato also stands out; even when the state presents the lowest percentage of berry production, strawberry stands out as a specialization crop (Bustamante-Lara *et al.*, 2020) and is one of the most relevant, with a production of 20 257 Mg in 2005 and 79 752 Mg in 2019 (SIAP, 2020). Based on the above, berries are considered one of the groups with high growth potential in the agricultural sector (González-Razo *et al.*, 2019). Strawberry production contributes 1.14 % of the national agricultural gross domestic product (GDP) and represents 2.19 % of fruit production in Mexico, while the raspberry, blackberry, and blueberry contribute 2.15 % of the national agricultural GDP and represent 1.83 % of fruit production (SAGARPA, 2017; SIAP, 2021).

Mexico's notable relevance in berry production places it third among the main producing countries (Figure 2). Its participation in the last 10 years stands out, with an increase in production from 392 635 Mg in 2011 to 1 337 208 Mg in 2019 (FAO, 2021). The main reasons for this boom are attributed to the increase in global demand (SAGARPA, 2017), high profitability, export opportunities (González-Razo *et al.*, 2019), and the health benefits of its consumption, which are associated with the nutraceutical

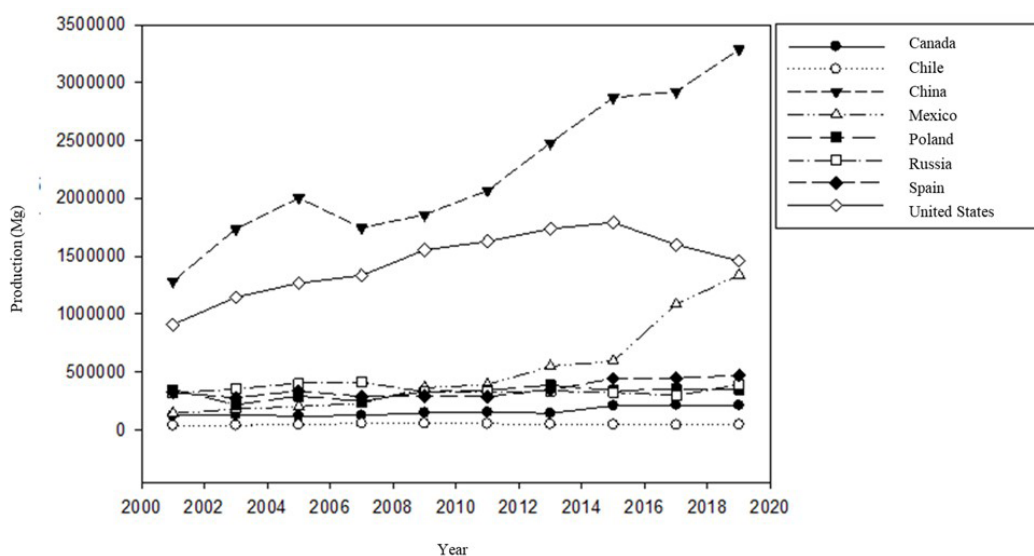
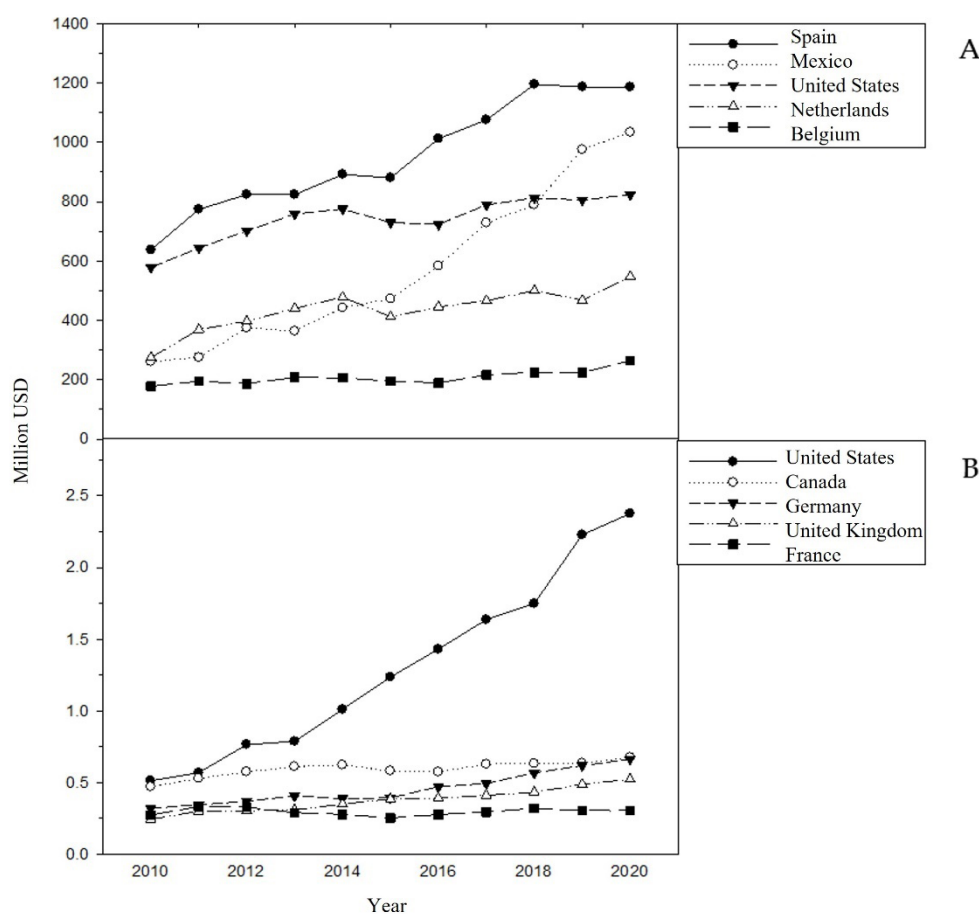


Figure 2. World production of berries (Own design with data from FAO, 2021).

and antioxidant properties that these fruits have (Beattie *et al.*, 2005; Sangiovanni *et al.*, 2017; Foito *et al.*, 2018).

### International trade

The value of world production of strawberries, raspberries, blueberries, and blackberries increased from \$13 766,594 to \$26 431,113 million USD between 2010 and 2020 (FAO, 2021), representing a 91 % growth in value, i.e., the value of berry production has doubled in 10 years. In Mexico, in 2020, 244 333 Mg of these products were exported, representing a value of \$1 033.328 million USD, which placed it second in the world above the USA. In 2020, this value represented \$823.470 million USD, and Spain ranked first with \$1 186.370 million USD (INTRACEN, 2021) (Figure 3).



**Figure 3.** Evolution of exports and imports of raspberries (*Rubus idaeus* L.), strawberries (*Fragaria* spp.), blackberries (*Rubus ulmifolius* Schott), and blueberries (*Vaccinium* spp.) in the most commercialized countries. A: exports; B: imports (own design with data from FAO, 2021; INTRACEN, 2021).

Berries have a high export potential in the Mexican agricultural sector, being the third most exported agricultural product. Mexico exports 52.21 % of its strawberry production and 41 % of its raspberry, blackberry, and mulberry production to the international market. The main destination for strawberry exports is the USA (99 %), and for raspberry, blackberry, and mulberry, the main export destinations are the USA (91 %) and the United Kingdom (2.6 %) (SAGARPA, 2017; INTRACEN, 2021). Thus, Mexico has established itself as the most important supplier of fresh strawberries in the U.S. market (Suh *et al.*, 2017; González-Razo *et al.*, 2019).

The USA is the main importer of strawberries. In 2020, it reported \$2 376 851 thousand USD as the value of these imports (Figure 3). Its main suppliers are Mexico, Peru, and Chile (INTRACEN, 2021). U.S. demand for strawberries increases in winter, which represents a great opportunity for Mexican exports (Wu *et al.*, 2017).

#### Export Comparative Advantage (VCE)

From 2001 to 2019, the export comparative advantage index of the set of Mexican berries selected for the present study was greater than 1, suggesting that Mexico has a comparative export advantage for these products (Table 2). In addition, the trend of Mexican berry exports has continued to grow steadily.

**Table 2.** Mexico's comparative export advantage (VCE) of berries from 2001 to 2019 (FAO, 2021; INTRACEN, 2021).

Year	Exports of berries in Mexico*	Agricultural exports in Mexico*	Exports of berries in the world*	World agricultural exports*	VCE
2001	64 815	3 649 880	760 905	115 293 122	0.99
2002	80 246	3 531 805	918 530	123 519 781	1.12
2003	102 805	4 231 334	1 106 503	143 027 998	1.14
2004	96 158	4 893 186	1 314 155	163 147 546	0.89
2005	164 996	5 228 115	1 429 805	175 081 050	1.35
2006	252 664	6 057 216	1 538 608	193 420 868	1.66
2007	299 538	6 870 670	1 833 168	247 661 878	1.77
2008	228 194	7 443 551	2 239 395	302 663 121	1.42
2009	191 617	7 283 816	2 142 532	268 114 459	1.19
2010	260 817	7 997 469	2 219 833	295 182 415	1.47
2011	275 639	9 356 848	2 626 766	363 041 498	1.40
2012	374 288	9 859 412	2 778 125	368 263 236	1.62
2013	363 946	10 847 073	2 932 859	389 915 095	1.50
2014	442 203	11 768 465	3 132 163	404 580 705	1.58
2015	472 588	12 640 450	3 031 399	384 203 452	1.56
2016	583 483	14 814 859	3 189 187	387 087 127	1.56
2017	728 795	15 990 551	3 504 567	415 835 025	1.69
2018	789 060	16 154 814	3 825 410	425 478 288	1.69
2019	977 780	17 155 888	3 904 307	428 264 646	1.83

\*\$ thousand USD.

### Import Comparative Advantage (VCI)

The negative results of the import comparative advantage (Table 3) may indicate that Mexico does not have a comparative import advantage in terms of global berry imports, despite being primarily an exporting country.

**Table 3.** Mexico's comparative import advantage (VCI) of berries from 2001 to 2019 (FAO, 2021; INTRACEN, 2021).

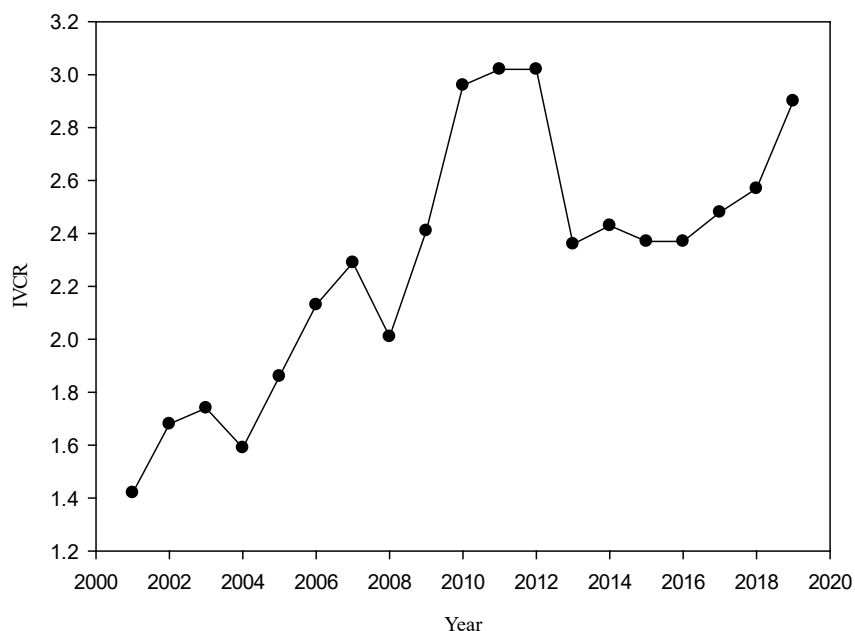
Year	Imports of berries in Mexico*	Agricultural imports in Mexico*	Berry imports in the world*	Agricultural imports in the world*	VCI
2001	13 226	3 119 941	851 261	131 439 019	-0.43
2002	14 628	3 331 799	1 052 757	138 549 528	-0.56
2003	14 535	3 435 060	1 228 356	162 158 796	-0.60
2004	14 543	3 675 526	1 468 558	186 686 531	-0.70
2005	18 290	3 579 455	1 662 144	197 959 165	-0.51
2006	24 909	4 596 848	1 894 445	221 330 701	-0.47
2007	26 838	5 463 952	2 248 298	276 726 540	-0.51
2008	31 218	7 221 735	2 618 551	340 709 314	-0.59
2009	14 029	5 361 899	2 583 969	297 418 449	-1.22
2010	11 520	5 669 366	2 855 112	321 406 063	-1.50
2011	14 395	8 301 154	3 309 295	388 589 936	-1.62
2012	20 677	8 851 433	3 707 792	397 854 095	-1.41
2013	29 437	7 499 647	3 907 775	427 639 365	-0.86
2014	31 188	7 437 976	4 225 176	435 262 097	-0.85
2015	34 179	7 304 893	4 377 137	420 456 580	-0.82
2016	38 413	7 483 860	4 711 699	418 746 425	-0.80
2017	42 963	7 979 745	5 300 539	454 117 061	-0.79
2018	46 853	8 844 358	5 799 712	465 960 825	-0.87
2019	42 567	8 836 065	6 389 588	467 319 059	-1.06

\*\$ thousand USD.

### Revealed Comparative Advantage Index (VCR)

Once the above analyses were carried out, the index of revealed comparative advantage was obtained (Figure 4). The result is interpreted as follows: if the VCR is greater than one, it means that there is a revealed comparative advantage in the product; if it is less, the country has a comparative disadvantage. The higher the value of this index, the higher the country's degree of specialization in this product and, therefore, the greater the competitiveness (Arias-Segura and Segura-Ruiz, 2004).

According to the results obtained, the VCR was greater than zero in the period analyzed, indicating that Mexico presents an important competitive position in the global market of berries and that berry exports exceed imported volumes. One of the factors influencing the high production of Mexican strawberries is the advantage represented by the cost and supply of labor, which contributes to commodity growth (Wu *et al.*, 2017).



**Figure 4.** Mexico's revealed comparative advantage (VCR) index in the global berry market from 2001 to 2019.

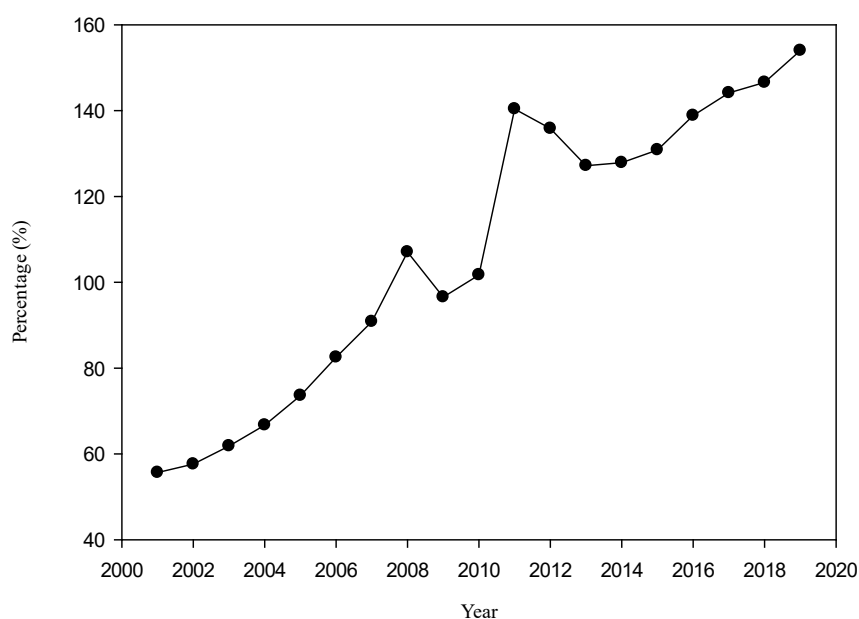
The historical behavior of the VCR indicates that Mexico's revealed comparative advantage has increased. According to Arias-Segura and Segura-Ruiz (2004), this reflects a country's ability to compete in the international market. Therefore, it is assumed that Mexico exports those goods for which it has a comparative advantage, in this case berries, a situation that helps guide investment and trade decisions and take advantage of international demand and supply for the product in question.

Mexico's successful positioning in berry marketing is related to its proximity to the U.S. market, which represents its main export destination (González-Ramírez *et al.*, 2020; Ramírez-Padrón *et al.*, 2020), and due consequently to the facilities provided by trade agreements (Ávila-Arce and González-Milán, 2012). In contrast, the positive impact represented by the increasing imports from Mexico by the USA, specifically in the strawberry industry, has generated greater challenges in the U.S. domestic market (Suh *et al.*, 2017). Strawberry exports to the United States represent the highest value and volume relative to other export destinations (Bustamante-Lara *et al.*, 2020).

Mexico has kept a comparative advantage in strawberry exports during the period analyzed, achieving specialization with a growing trend in the international market (Bustamante-Lara *et al.*, 2020). It is necessary to maintain this trend so that Mexico can keep and improve this advantage over other countries. According to Wu *et al.* (2017), despite the imminent advantage that the U.S. market represents for Mexican strawberry exports, it will be necessary to consider a diversification of export destinations to make trade more sustainable for both countries and avoid possible damage to their respective industries.

### Trade openness index

Trade openness is understood as a country's capacity to successfully insert itself into the international market. It acts simultaneously with competitiveness through the measurement of trade flows, that is, a country's participation in the international market, which is established through indicators such as the index of revealed comparative advantage (Quintero-Ramírez *et al.*, 2020). The index of trade openness of the Mexican agricultural sector has been increasing during the study period (2001–2019), which possibly represents a potential development market abroad (Figure 5).



**Figure 5.** Index of trade openness of berries in Mexico from 2001 to 2019 (in \$ thousand USD).

The values obtained in this research indicate that Mexico's productive capacity allows it to meet the needs of domestic demand for berries and be competitive in the international market (Ramírez-Padrón *et al.*, 2016). There is a positive trade balance derived from a higher value of exports compared to agricultural imports, which in turn has generated an increase compared to agricultural GDP. According to Ayala-Garay *et al.* (2012), Mexico's trade openness is growing at an accelerated pace due to the trade increase with the rest of the world. On the other hand, Bustamante-Lara *et al.* (2020) indicate that trade liberalization has allowed the levels of specialization and competitiveness of strawberries to increase since international trade has an impact on the specialization of production, which is why diversification of export destinations should be considered.

## CONCLUSIONS

Berries represent products that have gained worldwide relevance in the last two decades, related to their commercial value and health benefits. Mexico's climatic characteristics and geographic location have positioned it as one of the most important countries in the production and marketing of these products, among which strawberries and raspberries stand out and strengthen the competitiveness of the Mexican agricultural sector.

The growing demand for berries strengthens Mexico's competitive advantage in domestic and international markets. This is reflected in a positive and growing comparative advantage, which makes it highly competitive with the leading countries in the production and export of these products. Within the group of berries analyzed, strawberries represent Mexico's largest volume export. The USA is the main destination for Mexican exports.

## REFERENCES

- Aksoy MA. 2005. Global agricultural trade policies. In Aksoy MA, Beghin JC. (eds.), *Global Agricultural Trade and Developing Countries*. World Bank: Washington, DC, USA, pp: 37–53. <https://doi.org/10.1596/0-8213-5863-4>
- Arias-Segura J, Segura-Ruiz O. 2004. Índice de ventaja comparativa revelada: un indicador del desempeño y de la competitividad productivo-comercial de un país. *InterCambio, Área de Comercio y Agronegocios* 4: 1–10.
- Ávila-Arce A, González-Milán D de J. 2012. La competitividad de las fresas (*Fragaria* spp.) mexicanas en el mercado nacional, regional y de Estados Unidos. *Agricultura, Sociedad y Desarrollo* 9 (1): 17–27.
- Ayala-Garay AV, Schwentesius-Rindermann R, Carrera-Chávez B. 2012. Vegetables in Mexico: From U.S. competitiveness and opportunities for development. *Journal of Globalization, Competitiveness, and Governability* 6 (3): 70–88. <https://doi.org/10.3232/gcg.2012.v6.n3.04>
- Ayvar-Campos FJ, Navarro-Chávez JCL, Delfín-Ortega OV. 2018. Competitividad y productividad del sector agropecuario mexicano en APEC, 1980-2015. *Portes, Revista Mexicana de Estudios sobre la Cuenca del Pacífico* 12 (23): 7–30.
- Beattie J, Crozier A, Duthie, G. 2005. Potential health benefits of berries. *Current Nutrition and Food Science* 1 (1): 71–86. <https://doi.org/10.2174/1573401052953294>
- Bustamante-Lara TI, Vargas-Canales JM, Díaz-Sánchez F, Rosas-Vargas R. 2020. Especialización y competitividad en el sector agrícola mexicano: caso fresa. *Agro productividad* 13 (8): 31–37. <https://doi.org/10.32854/agrop.vi.1697>
- Bustillos-Durán S. 2015. Competitividad del sector agropecuario en México: implicaciones y retos México. *Nóesis - Revista de Ciencias Sociales y Humanidades* 24 (48): 233–237. <https://doi.org/10.20983/noesis.2015.2.10>
- Coronado-García MA, García-Porchas M, Santiago-Hernández VG, Córdova-Yañez A, Vásquez-Navarro RA. 2014. La zarzamora, un mercado potencial para los productores agropecuarios de la Sierra de Sonora. *Revista Mexicana de Agronegocios* 34: 784–794.
- Cruz-Delgado D, Leos-Rodríguez JA, Altamirano-Cárdenas JR. 2013. México: factores explicativos de la producción de frutas y hortalizas ante la apertura comercial. *Revista Chapingo Serie Horticultura* 19 (3): 267–278

- FAO (Food and Agriculture Organization). 2021. FAOSTAT. Food and agriculture data. Food and Agriculture Organization. Rome, Italy. <https://www.fao.org/faostat/en/#home> (Retrieved: October 2021).
- Foito A, McDougall GJ, Stewart D. 2018. Evidence for health benefits of berries. *Annual Plant Reviews* 1: 1–43. <https://doi.org/10.1002/9781119312994.apr0600>
- González-de Mejía E, Johnson MH. 2017. Anthocyanins from berries: Chemistry and roles in inflammation and diabetes. In Jayaprakasha GK, Bhimanagouda SP. (eds.), *Nutraceuticals and Functional Foods*. United Nations Educational, Scientific and Cultural Organization: Singapore. 354 p.
- González-Ramírez MG, Santoyo-Cortés VH, Arana-Coronado JJ, Muñoz-Rodríguez M. 2020. The insertion of Mexico into the global value chain of berries. *World Development Perspectives* 20: 100240. <https://doi.org/10.1016/j.wdp.2020.100240>
- González-Razo F de J, Rebollar-Rebollar S, Hernández-Martínez J, Morales-Hernández JL, Ramírez-Abarca O. 2019. Situación actual y perspectivas de la producción de berries en México. *Revista Mexicana de Agronegocios* 44: 260–272.
- Housni FE, Lares-Michel M, Aguilera-Cervantes VG, Guizar-Mateos I, Bracamontes-del Toro H, Michel-Nava RM. 2018. Impacto de la producción de berries sobre el comportamiento alimentario en una población de Jalisco, México. *Revista Mexicana de Trastornos Alimentarios* 9 (1): 11–23. <https://doi.org/10.22201/fesi.20071523e.2018.1.463>
- INTRACEN (International Trade Center). 2021. Trade statistics for the international development of companies. International Trade Center. Geneva, Switzerland. <https://www.trademap.org> (Retrieved: November 2021).
- Martínez-Borrego E. 2016. Agricultura, sustitución de cultivos y exportaciones en la zona metropolitana de León, Guanajuato, México. *Carta Económica Regional* 27 (116): 112–140.
- Muratalla-Lúa A, Jaen-Contreras D, Arévalo-Galarza L. 2018. La producción de frambuesa y zarzamora en México. *Agro Productividad* 6 (5): 3–12.
- Oszmiański J, Nowicka P, Teleszko M, Wojdyło A, Cebulak T, Oklejewicz K. 2015. Analysis of phenolic compounds and antioxidant activity in wild blackberry fruits. *International Journal of Molecular Sciences* 16 (12): 14540–14553. <https://doi.org/10.3390/ijms160714540>
- Porter ME. 2011. ¿Qué es la estrategia? *Harvard Business Review* 89 (11): 100–117.
- Quintero-Ramírez JM, Omaña-Silvestre JM, Ramírez-Padrón LC. 2020. Análisis de indicadores de ventajas comparativas reveladas: competitividad de las exportaciones de fresa (*Fragaria* spp.) mexicana. *Revista de Desarrollo Económico* 7 (24): 13–19. <https://doi.org/10.35429/jed.2020.24.7.13.19>
- Ramírez-Padrón LC, Caamal-Cauich, I, Pat-Fernández VG, Martínez-Luis D. 2016. Índices de competitividad de la fresa (*Fragaria vesca* L.) de México en el mercado mundial. *Agroproductividad* 9 (5): 29–34.
- Ramírez-Padrón LC, Caamal-Cauich I, Pat-Fernández VG, Martínez-Luis D, Pérez-Fernández A. 2020. Análisis de los indicadores de competitividad de las exportaciones de fresa mexicana. *Revista Mexicana de Ciencias Agrícolas* 11 (4): 815–827. <https://doi.org/10.29312/remexca.v11i4.2049>
- SAGARPA (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación). 2017. Planeación agrícola nacional 2017-2030. Gobierno de México. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Ciudad de México, México. <https://www.gob.mx/agricultura/acciones-y-programas/planeacion-agricola-nacional-2017-2030-126813> (Retrieved: January 2022).

- Sánchez-Rodríguez G. 2008. La red de valor de la zarzamora. El cluster de Los Reyes Michoacán, un ejemplo de reconversión competitiva. Sistema de Inteligencia de Mercados. Fundación Produce Michoacán A. C.: Morelia, México.
- Sangiovanni E, Fumagalli M, dell'Agli M. 2017. Berries: Gastrointestinal protection against oxidative stress and inflammation. *In* Gracia-Sancho J, Salvadó J. (eds.), *Gastrointestinal Tissue, Oxidative Stress and Dietary Antioxidants*. Academic Press: Milan, Italy, pp: 243–258. <https://doi.org/10.1016/b978-0-12-805377-5.00018-7>
- SIAP (Servicio de Información Agroalimentaria y Pesquera). 2020. Sistema de información agroalimentaria de consulta SIACON, versión 2020. Gobierno de México, Secretaría de Agricultura y Desarrollo Rural, Servicio de Información Agroalimentaria y Pesquera. Ciudad de México, México. <https://www.gob.mx/siap/documentos/siacon-ng-161430> (Retrieved: September 2021).
- SIAP (Servicio de Información Agroalimentaria y Pesquera). 2021. Producción agrícola. Gobierno de México, Servicio de Información Agroalimentaria y Pesquera. Ciudad de México, México. <https://www.gob.mx/siap/acciones-y-programas/produccion-agricola-33119> (Retrieved: September 2021).
- Souza AVD, Rodrigues RJ, Gomes EP, Gomes GP, Vieites RL. 2015. Bromatological characterization of blackberry fruits and jellies. *Revista Brasileira de Fruticultura* 37 (1): 13–19. <https://doi.org/10.1590/0100-2945-037/14>
- Suh DH, Guan Z, Khachatryan H. 2017. The impact of Mexican competition on the U.S. strawberry industry. *International Food and Agribusiness Management Review* 20 (4): 591–604. <https://doi.org/10.22434/ifamr2016.0075>
- Vollrath TL. 1991. A theoretical evaluation of alternative trade intensity measures of revealed comparative advantage. *Weltwirtschaftliches Archiv* 127 (2): 265–280.
- Wu F, Guan Z, Arana-Coronado JJ, García-Nazariega M. 2017. An overview of strawberry production in Mexico. *UF/IFAS Food and Resource Economics*: FE1014.

## RICE (*Oryza sativa* L.) SELF-SUFFICIENCY IN MEXICO: IS IT POSSIBLE TO ACHIEVE IT?

Jenny Virgilio-León<sup>1</sup>, José Alberto García-Salazar<sup>1\*</sup>, Saturnino Mora-Flores<sup>1</sup>, Roberto García-Mata<sup>1</sup>, Rocío Ramírez-Jaspeado<sup>2</sup>

<sup>1</sup>Colegio de Postgraduados Campus Montecillo. Programa de Economía. Carretera México- Texcoco km 36.5, Montecillo, Texcoco, State of Mexico, Mexico. C. P. 56264.

<sup>2</sup>Universidad Autónoma Chapingo. División de Ciencias Económicas-Administrativas. Carretera México- Texcoco km 38.5, Chapingo, Texcoco, State of Mexico, Mexico. C. P. 56230.

\* Author for correspondence: jsalazar@colpos.mx

### ABSTRACT

Given the significance of rice in the Mexican diet and the country's dependence on imports to meet domestic demand, an examination of the food self-sufficiency index (SSI) for rice, which was 16.9 % in 2021, is required. The goal of this study was to examine the possibility of increasing the SSI to 66 % through crop area and yield increases, as well as to identify the most competitive regions in irrigated and rainfed agriculture under free trade conditions. A spatial equilibrium model that considered yield and potential area was obtained to analyze three scenarios that would place the SSI at 21, 46, and 66 %. The results show that to reach an SSI of 66 %, production would have to rise to 1139.7 thousand Mg, with 144.6 thousand ha of irrigated land and 18.2 thousand ha of rainfed areas, and an average yield of 7.4 and 4.2 Mg ha<sup>-1</sup>, respectively. The rice-producing states with the highest growth potential would be Nayarit, Campeche, and Michoacán, which have the potential to increase the cultivated area by more than 75 000 ha. Other regions with potential include Veracruz, Colima, and Jalisco. Due to the vulnerability of the domestic market to exogenous international changes resulting from its dependence on imports, it is recommended that the necessary measures be implemented to increase SSI for rice.

**Keywords:** food self-sufficiency, production, import, yield, area.

### INTRODUCTION

Rice (*Oryza sativa* L.) is the third most consumed cereal in Mexico, after maize and wheat. In 2021, per capita rice consumption was 9.1 kg, with a national production of 257 thousand Mg, a cultivated area of 41 thousand ha, a yield of 6.4 Mg ha<sup>-1</sup>, and a production value of \$1341 million MXN. The main producing states were Campeche, Nayarit, and Michoacán with 28, 20.5, and 13.2 % of total production, respectively (SIAP, 2022a). From 1961 to 2020, rice consumption showed an average annual growth rate (AAGR) of 2.4 %. The North American Free Trade Agreement (NAFTA), which allowed duty-free imports and import quotas, was the most important factor behind the increase in rice consumption, as low rice prices led to an increase in demand.

**Citation:** Virgilio-León J, García-Salazar JA, Mora-Flores S, García-Mata R, Ramírez-Jaspeado R. 2024. Rice (*Oryza sativa* L.) self-sufficiency in Mexico: Is it possible to achieve it?. *Agrociencia* 58(5): 609-626. <https://doi.org/10.47163/agrociencia.v58i5.3056>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: August 08, 2023.

Approved: May 14, 2024.

**Published in Agrociencia:**

July 29, 2024.

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



Food security and supply have been covered by domestic production and imports. From 1961 to 2020, rice imports experienced an average annual growth of 14.4 %, from 0.4 to 1 114.5 thousand Mg. From 1961 to 1985, production had a positive performance; however, from 1985 onwards, a negative trend was observed. From being self-sufficient in the 1961–1990 period, Mexico became a rice importer. During the 2016–2020 period, it had a Food Dependency Index (FDI) of 83.1 % and a Food Self-Sufficiency Index (SSI) of 16.9 %. The FDI and SSI indicate the percentage of total consumption that is supplied by imports and domestic production, respectively, which means that less than one-fifth of consumption was supplied by domestic production in that period (Table 1).

Food self-sufficiency is defined as the degree to which a country can meet its food needs from its own production, as measured by the rate of self-sufficiency (FAO, 1999), or as the ability of a nation to produce the majority of its food requirements (FAO, 2023a). Otero *et al.* (2013) defined it as the ability of a country to provide basic foodstuffs to its population without relying on imports exceeding 20 % of its domestic supply.

The high FDI for rice in Mexico is due to two factors: increasing consumption and decreasing production. The latter experienced an annual decline of -0.2 % during the 1961–2020 period, caused by a decrease in the production area, which showed an annual decline of -1.9 % from 1961 to 2020, while the yield had a positive growth of 1.7 % during the same period. To meet demand in 2021, imports of 1 016.4 thousand

**Table 1.** Food Dependency Index (FDI) and Food Self-Sufficiency Index (SSI) for palay rice in Mexico (FAO, 2023b).

Period	S ha	R Mg ha <sup>-1</sup>	P Mg	M Mg	X Mg	C Mg	FDI %	SSI %
1961–1965	137 132	2.3	314 050	6 025	8 825	311 251	1.9	98.1
1966–1970	152 534	2.5	387 537	10 140	6 100	391 577	2.6	97.4
1971–1975	177 945	2.7	486 234	33 188	3 727	515 695	6.4	93.6
1976–1980	147 979	3.2	474 342	38 570	8 855	504 057	7.7	92.3
1981–1985	161 458	3.6	588 213	141 478	0	729 690	19.4	80.6
1986–1990	139 155	3.6	502 737	101 007	57	603 687	16.7	83.3
1991–1995	80 077	4.5	353 819	352 832	114	706 537	49.9	50.1
1996–2000	93 696	4.4	413 505	526 798	2 697	937 606	56.2	43.8
2001–2005	56 714	4.6	259 356	717 251	919	975 688	73.5	26.5
2005–2010	57 537	4.7	267 204	809 213	5 527	1070 890	75.6	24.4
2011–2015	36 050	5.5	200 040	944 118	1 236	1142 922	82.6	17.4
2016–2020	42 839	6.3	268 786	1168 013	30 776	1406 022	83.1	16.9
2021	40 280	6.4	257 041	1016 418	17 364	1256 095	80.9	19.1
GR <sub>1961-20</sub> (%)	-67.5	173.0	-11.3	314 889	157.7	324.0	74 190	-79.3
AAGR <sub>1961-20</sub> (%)	-1.9	1.7	-0.2	14.4	1.6	2.4	11.6	-2.6

S: harvested area; R: yield; P: production; M: imports; X: exports; C: consumption; GR: growth rate; AAGR: average annual growth rate.

Mg were required, totaling \$412 million USD; 84.6 % of imports came from the USA. The highest imports took place in February, April, August, September, and December (10.0, 10.8, 10.9, 10.6, and 10.1 %, respectively), while the months with the highest harvests were June and November, with 16.5 and 30.1 % of national production (SIAP, 2022a).

Which factors explain the fall in rice production? Schwentesius and Gómez-Cruz (1999) identified macroeconomic policy (less support for production due to the withdrawal of the state from its economic functions), trade liberalization, and the difference in price and subsidy policy between the US and Mexico as the factors that caused the decrease in cultivated area. Ireta-Paredes *et al.* (2015) indicated that the causes explaining the loss of competitiveness of the rice producer were the exchange rate, high interest rates, the decrease in subsidies, the lack of integration of the production chain, the increase in production costs, and the decrease in the producer's price. Another contributing factor was water scarcity in some regions, with 62 % of irrigated rice production established in regions with high water stress (Lerma-Santiago-Pacific, North Pacific, and Balsas) (CEDRSSA, 2015).

During the last decades, Mexico's grain food security policy has taken advantage of the low prices on the international market and has allowed an increasing percentage of consumption to be supplied by imports. Food security is oriented towards the physical and economic accessibility of sufficient, safe, and nutritious food to meet dietary needs (FAO, 2009). To encourage the production of staple crops, the Mexican government has launched the Guarantee Prices Program and the Fertilizer for Well-Being Program, whose target populations include small and medium-sized rice producers.

Should Mexico continue to rely on imports to secure rice consumption? According to the FAO, a country must be able to produce at least 75 % of the food it consumes to provide food security for its population (Curiel, 2013). Otero *et al.* (2013) critiqued the notion of food security that has been central to the discourse of opening up the domestic agricultural sector and showed that food dependency has been stronger in developing countries than in advanced capitalist countries. As an example of this, Mexico adopted neoliberal policies and became dependent on imports of basic foodstuffs, which represents a major risk to food security.

According to SADER (2019), the advantages of food self-sufficiency include protecting the country from changes in international trade and price fluctuations. This generates a supply system that, in addition to securing products, considers production, transformation, trade, and financial and technological services, which saves and generates its own food system, caring for the environment, and improving producers' living conditions.

Ray *et al.* (2013) indicated that to meet global rice demand, production needs to double, implying that the global rice growth rate should be 2.4 %; however, production is actually increasing at a rate of 1 % per year, which is insufficient to meet the projected demand in 2050. Ávila (1982) determined that an improvement in technology was not sufficient to supply the national demand for rice and that it would be necessary

to increase the area under cultivation. To achieve food security, Ray *et al.* (2013) concluded that it was better to increase crop yields rather than the area cultivated. To increase yields, Twine (2023) suggested focusing efforts on genetic improvement, seed systems, market intelligence, and strengthening co-ownership.

According to Fathonah and Mashilal (2021), in Pakistan and India, land availability was shown to be an indicator of rice production and self-sufficiency, while in Iran it was increased irrigation efficiency. In China, optimizing self-sufficiency increased capital and relationships between large and profitable enterprises, as well as the creation of policies that included incentives for grain-producing areas, subsidies, agricultural education, and supervision of new farms. Land yields increased in eight African countries, but self-sufficiency will not be achieved by 2025. In Indonesia, food self-sufficiency was promoted through improvements in agricultural infrastructure, reduction of import levels, and revision of government purchase prices, as well as extensification, minimization of post-harvest losses, rice export intensification, and conversion of agricultural land. Of the variables assessed (labor, capital, and area), area has a more significant impact on the growth rate of rice production in Indonesia (Fathonah and Mashilal, 2021).

The objective of this research was to analyze the possibility of achieving an SSI of 66 % through increases in crop area and yield, as well as to identify the most competitive irrigated and rainfed areas for the production of this crop in the context of free trade. The hypothesis is that Mexico can achieve an SSI of 66 %.

## MATERIALS AND METHODS

A spatial equilibrium model was used to represent the disaggregated rice market in Mexico. The formulation of the model was based on Takayama and Judge (1971) and Salin *et al.* (2000). Elements of the structure of the Mexican rice market and its relationship with US exports were analyzed. Fuller *et al.* (2003) indicated that the elimination of tariffs would affect producer prices and production in Mexico, and García-Salazar (2015) presented the methodological basis for designing the model and estimating potential production. Other authors, such as García-Salazar *et al.* (2023), used the Food Dependency Index in terms of consumption, production, and exports to determine the necessary growth in area and yield at the national level to decrease imports.

The model considered  $i(1,2,\dots,I = 12)$  palay rice producing regions;  $p(1,2,\dots,P = 13)$  rice milling regions;  $j(1,2,\dots,J = 32)$  polished rice consuming regions;  $m(1,2,\dots,M = 5)$  ports and borders of entry for palay rice;  $n(1,2,\dots,N = 6)$  ports and borders of entry for polished rice; and  $e(1,2 \text{ and } 3 = E)$  ports of exit of polished rice. The rice-producing regions considered were Nayarit, Campeche, Michoacán, Veracruz, Colima, Tamaulipas, Jalisco, Tabasco, Morelos, Guerrero, Chiapas, and State of Mexico (SIAP, 2022b). The rice-processing regions were Campeche, Colima, Guanajuato, Jalisco, State of Mexico, Michoacán, Morelos, Nayarit, Nuevo León, Puebla, Sinaloa, Tamaulipas, and Veracruz

(INEGI, 2021a). The consumer regions were represented by the 31 Mexican states and Mexico City. The ports and borders of entry for palay rice were Veracruz, Tuxpan, Altamira, Nuevo Progreso, and Nuevo Laredo (SIAP, 2021). The ports and borders of entry for polished rice were Veracruz, Manzanillo, Tijuana, Piedras Negras, Ciudad Juárez, and Nuevo Laredo (SIAP, 2021). The ports of export of polished rice were Veracruz, Manzanillo, and Nuevo Laredo (SIAP, 2021).

The objective function of the model maximizes Net Social Payoff and is equal to the sum of the area under the demand curve minus the area under the supply curve, plus the value of exports, minus the value of imports, minus profit and transportation costs:

$$\begin{aligned}
 Max\ NSP = & \sum_{j=1}^J \left[ \lambda_j y_j + \frac{1}{2} \omega_j y_j^2 \right] - \sum_{i=1}^I \left[ v_i x_i + \frac{1}{2} \eta_i x_i^2 \right] \\
 & + \sum_{e=1}^E [P_e x_e] - \sum_{m=1}^M [P_m x_m] - \sum_{n=1}^N [P_n x_n] - \sum_{p=1}^P [P_p x_p] - \sum_{i=1}^I \sum_{p=1}^P [C_{ip}^c x_{ip}^c] \\
 & - \sum_{p=1}^P \sum_{j=1}^J [C_{pj}^c x_{pj}^c + C_{pj}^f x_{pj}^f] - \sum_{p=1}^P \sum_{e=1}^E [C_{pe}^c x_{pe}^c + C_{pe}^f x_{pe}^f] \\
 & - \sum_{m=1}^M \sum_{p=1}^P [C_{mp}^c x_{mp}^c + C_{mp}^f x_{mp}^f] - \sum_{n=1}^N \sum_{j=1}^J [C_{nj}^c x_{nj}^c + C_{nj}^f x_{nj}^f] \tag{1}
 \end{aligned}$$

where  $\lambda_j$  and  $\omega_j$  represent the intercept and slope of the demand function;  $y_j$  is the quantity consumed of polished rice in  $j$ ;  $v_i$  and  $\eta_i$  are the intercept and slope of the supply function in  $i$ ;  $x_i$  is the quantity produced of palay rice in  $i$ ;  $P_m$  and  $x_m$  are the import price and the imported quantity of palay rice by  $m$ ;  $P_n$  and  $x_n$  are the import price and the imported quantity of polished rice by  $n$ ;  $P_e$  and  $x_e$  are the export price and the exported quantity of polished rice by  $e$ ;  $P_p$  and  $x_p$  are the profit cost and the profited quantity of rice in  $p$ ;  $C_{ip}^c$  and  $x_{ip}^c$  are the transportation cost and the quantity of palay rice shipped from  $i$  to  $p$  by truck;  $C_{pj}^c$  and  $x_{pj}^c$  are the transportation cost and the quantity shipped from  $p$  a  $j$  by truck;  $C_{pj}^f$  and  $x_{pj}^f$  are the transportation cost and the quantity shipped of  $p$  to  $j$  by rail;  $C_{pe}^c$  and  $x_{pe}^c$  are the transportation cost and the quantity shipped from  $p$  to  $e$  by truck;  $C_{pe}^f$  and  $x_{pe}^f$  are the transportation cost and the quantity shipped from  $p$  to  $e$  by rail;  $C_{mp}^c$  and  $x_{mp}^c$  are the transportation cost and the quantity of palay rice from  $m$  to  $p$  shipped by truck;  $C_{mp}^f$  and  $x_{mp}^f$  are the transportation cost and the quantity of palay rice from  $m$  to  $p$  shipped by rail;  $C_{nj}^c$  and  $x_{nj}^c$  are the transportation cost and the quantity from  $n$  to  $j$  shipped by truck; and  $C_{nj}^f$  and  $x_{nj}^f$  are the transportation cost and the quantity from  $n$  a  $j$  shipped by rail.

The shipment of polished rice from  $p$  and  $n$  to  $j$ , by truck and rail, is equal to or greater than the demand for polished rice in  $j$ :

$$\sum_{p=1}^P x_{pj}^c + \sum_{p=1}^P x_{pj}^f + \sum_{n=1}^N x_{nj}^c + \sum_{n=1}^N x_{nj}^f \geq y_j \quad (2)$$

The shipment of palay rice from  $i$  to  $p$  (discounting  $\delta$  moisture losses) plus shipments from  $m$  to  $p$ , by truck and rail, is equal to or greater than the quantity of rice polished by its processing coefficient  $\alpha$ :

$$\delta \left[ \sum_{i=1}^I x_{ip}^c \right] + \sum_{m=1}^M x_{mp}^c + \sum_{m=1}^M x_{mp}^f \geq X_p a_p \quad (3)$$

The shipment of polished rice from  $p$  to  $e$ , by truck and rail, is equal to or greater than the exported quantity of polished rice by  $e$ :

$$\sum_{p=1}^P x_{pe}^c + \sum_{p=1}^P x_{pe}^f \geq X_e \quad (4)$$

The shipment of polished rice from  $p$  to  $e$  and  $j$ , by truck and rail, is equal to or less than the quantity of milled rice in  $p$ :

$$\sum_{j=1}^J x_{pj}^c + \sum_{j=1}^J x_{pj}^f + \sum_{e=1}^E x_{pe}^c + \sum_{e=1}^E x_{pe}^f \leq x_p \quad (5)$$

The shipment of palay rice from  $i$  to  $p$ , by truck, is equal to or less than the quantity of palay rice produced in  $i$ .

$$\sum_{p=1}^P x_{ip}^c \leq x_i \quad (6)$$

The shipment of polished rice from  $n$  to  $j$  is equal to or less than the quantity of polished rice imported by  $n$ .

$$\sum_{i=1}^J x_{nj}^c + \sum_{j=1}^J x_{nj}^f \leq x_n \quad (7)$$

The shipment of palay rice from  $m$  to  $p$ , by truck and rail, is equal to or less than the imported quantity of palay rice by  $m$ .

$$\sum_{p=1}^P x_{mp}^c + \sum_{p=1}^P x_{mp}^f \leq x_m \quad (8)$$

The following equation sets the limit for imports of palay rice:

$$\mu x_m \geq \sum_{m=1}^M x_m \quad (9)$$

where  $\mu$  represents the SSI (%).

Finally, the non-negativity conditions are represented as follows:

$$y_j, x_i, \dots, x_{nj}^f, x_{pe}^f \geq 0 \quad (10)$$

A baseline model was validated for the year 2020. The endogenous variables considered were: production, consumption, imports of palay and polished rice, exports of polished rice, quantity of rice milled, and trade flows. To validate the model, the observed values (in terms of palay rice) of production, consumption, imports, irrigated and rainfed harvested area, and irrigated and rainfed yields were compared using the values estimated by the base model, which showed differences, in absolute terms, of less than 10 %.

To determine the most competitive areas, three scenarios were obtained: 1) changes in RR (irrigated yield), RT (rainfed yield), and ST (rainfed harvested area), keeping SR (irrigated harvested area) constant; 2) changes in RR, RT, and SR, keeping ST constant; and 3) changes in RR, RT, SR, and ST. In each scenario, increases in area and yield were made to set the SSI at 21, 46, and 66 %. Potential yield and area to produce rice were taken as upper limits. The most competitive regions would be those where production increases when the SSI increases.

To develop the scenarios, the following constraints were added to the model:

$$x_i = \sum_{i=1}^I SR_i * RR_i + \sum_{i=1}^I ST_i * RT_i \quad (11)$$

$$\sum_{i=1}^I SR_i \geq \sum_{i=1}^I SRO_i \quad (12)$$

$$\sum_{i=1}^I SR_i \leq \sum_{i=1}^I SRP_i \quad (13)$$

$$\sum_{i=1}^I ST_i \geq \sum_{i=1}^I STO_i \quad (14)$$

$$\sum_{i=1}^I ST_i \leq \sum_{i=1}^I STP_i \quad (15)$$

$$\sum_{i=1}^I RR_i \geq \sum_{i=1}^I RRO_i \quad (16)$$

$$\sum_{i=1}^I RR_i \leq \sum_{i=1}^I RRP_i \quad (17)$$

$$\sum_{i=1}^I RT_i \geq \sum_{i=1}^I RTO_i \quad (18)$$

$$\sum_{i=1}^I RT_i \leq \sum_{i=1}^I RTP_i \quad (19)$$

where for region  $i$ :  $SR_i$ ,  $ST_i$ ,  $RR_i$ , and  $RT_i$  are the irrigated and rainfed area and yield;  $SRO_i$ ,  $STO_i$ ,  $RRO_i$ , and  $RTO_i$  are the observed irrigated and rainfed area and yield; and  $SRP_i$ ,  $STP_i$ ,  $RRP_i$ , and  $RTP_i$  are the potential irrigated and rainfed area and yield.

Equation 11 indicates that rice production is equal to the production obtained under irrigation and rainfed conditions. Equations 12 to 15 set lower and upper limits to the rice area; the lower limit corresponds to the area observed in the year of analysis and the upper limit to the potential area. Similarly, equations 16 to 19 set lower and upper limits to the rice yield.

The data used is for the year 2020. The supply functions for palay rice and demand for polished rice by region were calculated using price elasticities of supply and demand, quantities produced and consumed, and producer and consumer prices (García-Salazar, 2015). Elasticities were taken from Vázquez-Alvarado and Martínez-Damián

(2015). The amount of palay rice produced by region was obtained from SIAP (2022b). A 15 % loss due to moisture was taken into account. To obtain the amount of rice consumed by region, the method proposed by García-Salazar (2015) was used. First, the Apparent National Consumption (CNA) of palay rice was obtained by adding imports to production and deducting exports. The CNA of polished rice resulted from multiplying the CNA of palay rice by its transformation coefficient plus the imported minus the exported quantities of polished rice. Regional consumption was obtained by multiplying the CNA of polished rice by a weight representing the population share of each region  $j$  (INEGI, 2021b).

The producer price was calculated by adding the import price of palay rice plus the cost of transportation from the port to the mill, minus the cost of transportation from the producing region to the mill, and minus the cost of drying. The consumer price was obtained by adding the import price of polished rice and the cost of transportation from the port to the consumption area. Import prices of palay and polished rice and export prices of polished rice by port or border were calculated by dividing their value by the quantity multiplied by the exchange rate in 2020. Rice beneficiation quantity, beneficiation cost, and drying cost were obtained from Mendoza-Mondragón (2022), while palay rice imports and polished rice imports and exports were obtained from SIAP (2021).

The cost of transportation by train was estimated with a distance matrix and the average tariff, including a fixed factor and a variable factor for the transportation of palay and polished rice (ARTF, 2020). To estimate the transportation cost per truck, a distance matrix was used; quotes were obtained using the GlobalMap Software trial version (GlobalMap, 2021) for transportation type T3-S2 with a load capacity of 30 Mg, adding 35 % to the cost for the carrier's profit.

Area, yield, and production by cycle (spring-summer and autumn-winter) and water regime were obtained from SIAP (2022b). Import, export, production, consumption, and processing ratio were obtained from FAO (2023b). The exchange rate was taken from Gobierno de México (2021) and the potential state area by water regime from SIAP (2023). The method proposed by García-Salazar and Skaggs (2015) was used to determine the potential yield. Potential yields by state were calculated using information on observed municipal yields. The potential yield in a district was assumed to be equal to the highest yield observed in the leading municipality (the one with the highest yield).

## RESULTS AND DISCUSSION

The validation of the model (Table 2) consisted of comparing the estimated values of the rice market variables with the observed values in 2020. The acceptance criterion for the base model is that the differences between observed and estimated should be less than  $\pm 10$  %. In this case, the estimated model underestimates production in Guerrero and the State of Mexico with 0.2 and 0.8 % and overestimates production in the State of

Jalisco, rainfed yield, and national consumption with 0.1, 0.1, and 0.4 %. The differences were less than 1 % for all the variables analyzed (Table 2); therefore, the model can be used to run scenarios. The base model estimated total production at 295.3 thousand Mg, of which 83.4 % was obtained in 35.1 thousand ha harvested under irrigation with a yield of 7 Mg ha<sup>-1</sup> and the rest in 12.4 thousand ha under rainfed conditions with a yield of 3.9 Mg ha<sup>-1</sup>. Domestic and import consumption reached values of 1.4 and 1.2 million Mg, with an SSI of 16 %.

The results of the scenarios (Table 3) show that in order to increase production and achieve an SSI of 21 %, the following options are available: a) 27.6 thousand ha in rainfed conditions, with a yield of 4.5 Mg ha<sup>-1</sup>, and 35.1 thousand ha in irrigated conditions, with a yield of 7.5 Mg ha<sup>-1</sup>; b) 45.5 thousand ha in irrigated conditions, with a yield of 7.3 Mg ha<sup>-1</sup>, and 12.5 thousand ha in rainfed conditions, with a yield of 4.6 Mg ha<sup>-1</sup>; and c) allocate 44.5 thousand ha in irrigation and 12.5 thousand ha in rainfed conditions with yields of 7.5 and 4.4 Mg ha<sup>-1</sup>. The above indicators would put production at 387.1 thousand Mg and imports would decrease to 1 135.4 thousand Mg. To increase production and achieve an SSI of 46 %, the following alternatives are available: a) harvest 131.3 thousand ha of rainfed land with a yield of 4.1 Mg ha<sup>-1</sup> and 35.1 thousand ha of irrigated land with a yield of 7.4 Mg ha<sup>-1</sup>; b) harvest 100.9 thousand

**Table 2.** Validation of the spatial equilibrium model of the rice market in Mexico for year 2020.

Region	Situation observed	Base model	Difference	Difference (%)
National production (Mg) <sup>†</sup>	295 338	295 336	-2	0.0
Campeche	72 230	72 215	-15	0.0
Colima	19 006	19 010	4	0.0
Chiapas	673	672	0	0.0
Guerrero	2362	2358	-4	-0.2
Jalisco	17 130	17 143	13	0.1
Mexico	334	331	-3	-0.8
Michoacán	30 056	30 047	-9	0.0
Morelos	8839	8837	-2	0.0
Nayarit	88 828	88 825	-3	0.0
Tabasco	7421	7421	0	0.0
Tamaulipas	14 040	14 040	0	0.0
Veracruz	34 419	34 435	16	0.0
Irrigated area (ha)	35 104	35 104	0	0.0
Rainfed area (ha)	12 449	12 450	1	0.0
Irrigated yield (Mg ha <sup>-1</sup> )	7.0	7.0	0	0.0
Rainfed yield (Mg ha <sup>-1</sup> )	3.9	4.0	0	0.1
National consumption (Mg) <sup>‡</sup>	1 433 884	1 434 639	756	0.1
Imports (Mg) <sup>‡</sup>	1 209 267	1 213 507	4240	0.4

<sup>†</sup>Palay rice production in the field; for comparison with palay rice imports, it is necessary to deduct the losses due to drying. <sup>‡</sup>Consumption and imports consider palay rice plus clean rice (in terms of palay rice).

**Table 3.** Increase of the Food Self-Sufficiency Index (SSI) of palay rice in Mexico through changes in yield and cultivated area.

Region	Model Basis	Scenarios			Change (%) <sup>§</sup>		
		E1	E2	E3	E1	E2	E3
SSI of 21 %							
Production (Mg) <sup>†</sup>	295 336	387 070	387 063	387 063	31.1	31.1	31.1
Irrigated area (ha)	35 104	35 104	45 451	44 535	0.0	29.5	26.9
Rainfed area (ha)	12 450	27 638	12 450	12 450	122.0	0.0	0.0
Irrigation yield (Mg ha <sup>-1</sup> )	7.0	7.5	7.2	7.5	6.6	3.4	6.3
Rainfed yield (Mg ha <sup>-1</sup> )	4.0	4.5	4.6	4.4	14.2	16.9	11.6
National consumption (Mg) <sup>‡</sup>	1 434 639	1 434 637	1 434 638	1 434 638	0.0	0.0	0.0
Domestic imports (Mg) <sup>‡</sup>	1 213 507	1 135 363	1 135 364	1 135 364	-6.4	-6.4	-6.4
SSI of 46 %							
Production (Mg) <sup>†</sup>	295 336	804 214	804 214	804 214	172.3	172.3	172.3
Irrigated area (ha)	35 104	35 104	100 990	69 568	0.0	187.7	98.2
Rainfed area (ha)	12 450	131 266	12 450	18 179	954.3	0.0	46.0
Irrigation yield (Mg ha <sup>-1</sup> )	7.0	7.4	7.4	7.3	6.1	5.4	4.6
Rainfed yield (Mg ha <sup>-1</sup> )	4.0	4.1	4.6	4.6	4.7	16.8	15.2
National consumption (Mg) <sup>‡</sup>	1 434 639	1 434 606	1 434 632	1 434 632	0.0	0.0	0.0
Domestic imports (Mg) <sup>‡</sup>	1 213 507	780 558	780 590	780 590	-35.7	-35.7	-35.7
SSI of 66 %							
Production (Mg) <sup>†</sup>	295 336	1 139 742	1 139 736	1 139 744	285.9	285.9	285.9
Irrigated area (ha)	35 104	35 104	142 168	144 642	0.0	305.0	312.0
Rainfed area (ha)	12 450	182 126	12 450	18 179	1362.9	0.0	46.0
Irrigation yield (Mg ha <sup>-1</sup> )	7.0	7.4	7.6	7.3	6.1	8.6	4.8
Rainfed yield (Mg ha <sup>-1</sup> )	4.0	4.9	4.6	4.2	23.7	16.9	7.2
National consumption (Mg) <sup>‡</sup>	1 434 639	1 434 476	1 434 604	1 434 632	0.0	0.0	0.0
Domestic imports (Mg) <sup>‡</sup>	1 213 507	495 083	495 217	495 235	-59.2	-59.2	-59.2

<sup>†</sup>Palay rice production in the field; for comparison with Palay rice imports, it is necessary to deduct the losses due to drying. <sup>‡</sup>Consumption and imports consider palay rice plus clean rice. <sup>§</sup>Change in % of the outcome of each scenario compared to the baseline model outcome.

ha of irrigated land with a yield of 7.4 Mg ha<sup>-1</sup> and 12.5 thousand ha of rainfed land with a yield of 4.6 Mg ha<sup>-1</sup>; and c) harvest 69.6 thousand ha of irrigated land and 18.2 rainfed with yields of 7.3 and 4.6 Mg ha<sup>-1</sup>. The above indicators put production at 804.2 thousand Mg and imports at 780.6 thousand Mg.

Increasing rice production and achieving an SSI of 66 % requires: a) harvesting 182.1 thousand ha in rainfed conditions, with a yield of 4.9 Mg ha<sup>-1</sup>, and 35.1 thousand ha in irrigated conditions, with a yield of 7.4 Mg ha<sup>-1</sup>; b) harvesting 142.2 thousand ha in irrigated conditions, with a yield of 7.6 Mg ha<sup>-1</sup>, and 12.5 thousand ha in rainfed conditions, with a yield of 4.6 Mg ha<sup>-1</sup>; and c) harvesting 144.6 thousand ha in irrigation and 18.2 in rainfed conditions, with yields of 7.3 and 4.2 Mg ha<sup>-1</sup>. The above indicators would place production at 1 139.7 thousand Mg and imports at 495.2 thousand Mg, thus reaching food self-sufficiency with an SSI of 66 %.

Regarding the area and yield required at the state level to increase the SSI of rice to 66 % (Table 4), the states of Nayarit, Campeche, Michoacán, Veracruz, and Jalisco would contribute 119.7 thousand ha, representing 82.7 % of the area harvested under irrigation, with Nayarit being the most competitive state in irrigation with 39.4 thousand ha. Campeche and Veracruz would contribute 14.7 thousand ha, representing 80.1 % of the area harvested under rainfed conditions. Campeche is the most competitive rainfed state and could allocate 123 000 ha to rice cultivation.

The national yield on irrigated harvested area would increase by 4.8 % (from 7 to 7.3 Mg ha<sup>-1</sup>). The states with the highest increases were Campeche, Colima, and Jalisco with 17, 8.7, and 8.5 %, respectively. For rainfed harvested areas, yields would increase by 7.2 % (from 4 to 4.2 Mg ha<sup>-1</sup>), with Veracruz, Colima, and Campeche showing increases of 27.3, 9.4, and 5.5 %, respectively.

The results indicate that it is possible to achieve rice self-sufficiency in Mexico. This is possible through the use of technological innovations, mainly the genetic improvement of seeds aimed at increasing production yields. García-Angulo *et al.* (2011) indicated that the Silverio variety can be grown rainfed or rainfed with relief irrigation in the humid tropics of the southeast (Veracruz, Oaxaca, Tabasco, Campeche, and Chiapas), in the sub-humid tropics of the northeast (Tamaulipas), and under irrigation in the dry tropics (Nayarit, Jalisco, Colima, and Michoacán). The average yield potential of this variety is 6 Mg ha<sup>-1</sup> in rainfed conditions, 7 Mg ha<sup>-1</sup> in rainfed conditions with relief irrigation, and 8 Mg ha<sup>-1</sup> under irrigation.

Álvarez-Hernández *et al.* (2018) found that long and thin grain rice lines were adapted to the Michoacán production area with yields between 8 and 8.5 Mg ha<sup>-1</sup> under irrigated conditions. Hernández-Aragón *et al.* (2019) demonstrated that the Pacific FL 15 and Gulf FL 16 rice varieties were stable in the ecosystems of both coasts of Mexico; they observed high yield potential in the Huasteca region, Morelos, Michoacán, Jalisco, and Nayarit with 9.8, 10.8, 12.02, 7.11, and 11.4 Mg ha<sup>-1</sup> under irrigated conditions, in Colima with 8.65 Mg ha<sup>-1</sup> under rainfed conditions with precarious irrigation, and in Tabasco with 4.05 Mg ha<sup>-1</sup> under rainfed conditions. Barrios-Gómez *et al.* (2018) evaluated the Morelos A-2016 variety (Morelos coarse grain type) under transplanting, direct sowing, and irrigation conditions, obtaining yields of 12 to 13.5 Mg ha<sup>-1</sup> at sites in Morelos, Mexico, Michoacán, Jalisco, and Guerrero. The above yields are similar to the potential yield established for each of the states in this research.

Ávila *et al.* (1982) indicated that, in order to increase production, it is not enough to increase yields, but it is necessary to increase the area. It has been reported that Mexico has 1.6 million ha of high productive potential and 2.9 million ha of medium productive potential for rice production (INIFAP, 2012). The greatest concentration of high productive potential is distributed over the Pacific Coastal Plain, the Sierra Madre del Sur, the Central American Cordillera, the Northern and Southern Coastal Plains of the Gulf of Mexico, the Eastern Neovolcanic Axis, and the Yucatan Peninsula. Mexico has 10.7 million ha of productive potential in the spring-summer cycle and 10.2 million ha in autumn-winter (SAGARPA, 2017). Turrent-Fernández *et al.* (2004)

**Table 4.** Area and yield required to increase the Food Self-Sufficiency Index (SSI) of rice by 66 % in Mexico.

Region	Model Basis	E3	Change	Model Basis	E3	Change
	Irrigated rice production (Mg)			Rainfed rice production (Mg)		
Campeche	47 485	236 437	188 952	24 730	49 015	24 285
Colima	9998	59 983	49 985	9011	9863	853
Chiapas	0	1911	1911	672	711	38
Guerrero	2131	8724	6593	227	234	6
Jalisco	17 143	61 437	44 294	0	0	0
Mexico	331	1248	917	0	0	0
Michoacán	30 047	112 435	82 388	0	0	0
Morelos	8837	33 132	24 295	0	0	0
Nayarit	83 771	342 353	258 582	5054	5054	0
Tabasco	7421	30 100	22 678	0	0	0
Tamaulipas	14 040	54 652	40 612	0	0	0
Veracruz	24 948	120 378	95 430	9485	12 079	2594
Total	246 153	1 062 789	816 636	49 179	76 955	27 776
	Irrigated area (ha)			Rainfed area (ha)		
Campeche	8145	34 658	26 513	6525	12 254	5729
Colima	1610	8886	7276	1774	1774	0
Chiapas	0	305	305	382	382	0
Guerrero	266	1089	823	118	118	0
Jalisco	2971	9814	6843	0	0	0
Mexico	52	120	68	0	0	0
Michoacán	3502	13 104	9602	0	0	0
Morelos	853	3198	2345	0	0	0
Nayarit	12 770	52 188	39 418	1337	1337	0
Tabasco	930	3772	2842	0	0	0
Tamaulipas	1950	7591	5641	0	0	0
Veracruz	2055	9916	7861	2314	2314	1
Total	35 104	144 642	109 538	12 449	18 179	5730
	Irrigated yield (Mg ha <sup>-1</sup> )			Rainfed yield (Mg ha <sup>-1</sup> )		
Campeche	5.8	6.8	1.00	3.8	4	0.20
Colima	6.2	6.8	0.60	5.1	5.6	0.50
Chiapas	5.8	6.3	0.50	1.8	1.9	0.10
Guerrero	8	8	0.00	1.9	2	0.10
Jalisco	5.8	6.3	0.50	0	0	0.00
Mexico	6.4	10.4	4.00	0	0	0.00
Michoacán	8.6	8.6	0.00	0	0	0.00
Morelos	10.4	10.4	0.00	0	0	0.00
Nayarit	6.6	6.6	0.00	3.8	3.8	0.00
Tabasco	8	8	0.00	0	0	0.00
Tamaulipas	7.2	7.2	0.00	0	0	0.00
Veracruz	12.1	12.1	0.00	4.1	5.2	1.10
Total	7	7.3	0.30	4	4.2	0.20

noted that south-southeast Mexico has abundant freshwater and arable land that remains idle in the autumn-winter cycle, making investment in hydro-agricultural infrastructure a very high priority.

Aguirre-Álvarez (2009) indicates that the Huasteca plain has hydraulic infrastructure to irrigate 143 000 ha with yields of 8 Mg ha<sup>-1</sup>. Moctezuma-López *et al.* (2021) identified 257.9 thousand ha with medium and high production potential and indicated that Tabasco could contribute 662.3 thousand Mg of rice if 105 thousand ha with high production potential were planted. This study shows that, although Tabasco has good land and water conditions, it does not significantly increase its cultivated area (22 678 ha) because other factors such as proximity to markets, transportation costs, and yields were considered. In the case of Tamaulipas, the increase in irrigated harvested area is 40.6 thousand ha.

Mexico has the potential to achieve food self-sufficiency. Torres and Rojas (2018) estimated that a harvested area of 184.1 thousand ha with a yield of 5.4 Mg ha<sup>-1</sup> is required to meet rice demand in 2030. This study suggests increases in yields and irrigated area, which will require investment in hydro-agricultural infrastructure, thus improving water productivity. According to Carracelas *et al.* (2021), by optimizing water use, this resource can be redirected to plant a larger area of rice or other crops, reducing the cost of irrigation and labor, as well as the crop's water footprint and environmental impact. These authors state that water productivity can be improved through: a) irrigation systems with controlled deficit, systematization of irrigation in the field, reduction of the irrigation period, use of polytubes, construction of taipans or parapets in advance, carrying out field work in advance (summer), reduction of losses through surface runoff, and percolation; b) the use of short-cycle varieties or those with a structure that allows better use of the available water; and c) the improvement and systematization of the water conduction systems in the field.

In a market economy, the producer will choose to plant rice based on profitability, which is equal to the income the producer receives from the sale of his product minus the cost of production, which the producer will pay for the inputs used in the production process; thus, government policies, market imperfections, and some macroeconomic policies will all have an impact on profitability. The Federal Government's Guarantee Price Policy, in effect since 2019, has a positive effect on producer income, and the Fertilizer for Welfare Program has a positive effect on profitability by lowering the acquisition cost of fertilizer, one of the primary inputs used in production. Market imperfections also have an impact on profitability. A local monopsony (the only industry buying palay rice in the region) may have a negative impact on the producer's income because the firm pays a low price for the raw material; similarly, a local monopoly (the only firm selling inputs in the region) may have a negative impact on production costs because it sells inputs at high prices.

Some macroeconomic policies would also have an impact on profitability; for example, a high interest rate would raise the cost of capital, thereby increasing the cost of production, as would an increase in the minimum wage paid to the producer's hired

labor. The exchange rate policy would also have an impact on profitability; the recent peso appreciation will reduce costs by lowering the price of imported inputs, but it may have a negative impact on income if the price of palay rice falls due to a drop in the international price of the rice.

Mexico must implement the necessary policies to ensure high profitability in rice production and support the goal of achieving self-sufficiency, which is justified by: a) the high per capita consumption of rice and the inclusion of the cereal in the basic food basket of Mexicans, where 76.5 % of the population has an income below the poverty line (CONEVAL, 2020); b) the high expenditure in foreign currency to import rice, which in 2021 was 412 million (SIAP, 2022a); c) the high vulnerability of the Mexican rice market to exogenous international changes (Covid-19, Russia-Ukraine war and fertilizer shortages); and d) the risk of probable increases in the international price of rice that would affect the low-income population, which spends more than 40 % of its income on food.

## CONCLUSIONS

Through the formulation of a spatial equilibrium model, we can conclude that Mexico has the potential to increase rice self-sufficiency. An increase in irrigated area of 109.5 thousand ha and rainfed area of 5.7 thousand ha, as well as increases in yields of 4.8 and 7.2 %, respectively, would raise the rice food self-sufficiency index to 66 %. The model's economic and logistical conditions indicate that the most competitive regions are Nayarit, Campeche, and Michoacán, which have the potential to increase the area by more than 75,000 ha; other entities with potential include Veracruz, Colima, and Jalisco.

## REFERENCES

- Aguirre-Álvarez E. 2009. Guía para producir arroz en la Planicie Huasteca. Folleto para productores No. MX-0-310305-52-03-14-10-13. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Ciudad de México, México. 46 p.
- Álvarez-Hernández JC, Tapia-Vargas LM, Hernández-Pérez A, Barrios-Gómez EJ, Pardo-Melgarejo S. 2018. Estabilidad productiva de las líneas avanzadas de arroz grano largo delgado en Michoacán, México. *Revista Mexicana de Ciencias Agrícolas* 9 (3): 629–637. <https://doi.org/10.29312/remexca.v9i3.606>
- ARTF (Agencia Reguladora de Transporte Ferroviario). 2020. Tarifa máxima de fletes 2020. Gobierno de México. Agencia Reguladora de Transporte Ferroviario. Ciudad de México, México. <https://www.gob.mx/artf/documentos/tarifas-ferroviarias-de-carga> (Retrieved: April 2021).
- Ávila DJA, Burguete HFC, Rosales AR, Álvarez JR, Hernández JM, Gordián RR, Vázquez CJA. 1982. Reacción de los agricultores de México a la política de precios agrícola. Proyecto: precios de garantía. Colegio de Postgraduados: Chapingo, México. 235 p.

- Barrios-Gómez EJ, Hernández-Aragón L, Tavitas-Fuentes L, Hernández-Arenas M, Canul-Ku J. 2018. Morelos A-2016: variedad de arroz de grano grueso. *Revista Mexicana de Ciencias Agrícolas* 9 (7): 1547–1552. <https://doi.org/10.29312/remexca.v9i7.680>
- Carracelas GG, Donoso GÑ, Becerra VV, Paredes MC, Uribe HC. 2021. Visión mundial del uso del agua en el cultivo de arroz (Cap.22). *In* Paredes CM, Becerra VV, Donoso ÑG. (eds.), 100 años del cultivo del arroz en Chile en un contexto internacional 1920–2020. Tomo II. Instituto de Investigaciones Agropecuarias: Chillán, Chile, pp: 611–628.
- CEDRSSA (Centro de Estudios para el Desarrollo Rural y la Soberanía Alimentaria). 2015. Reporte: la agricultura y la gestión sustentable del agua en México. Centro de Estudios para el Desarrollo Rural y la Soberanía Alimentaria. Ciudad de México, México. 19 p.
- CONEVAL (Consejo Nacional de Evaluación de la Política de Desarrollo Social). 2020. Medición de la pobreza. Resultados de pobreza en México a nivel nacional y por entidades federativas. Ciudad de México, México. <https://www.coneval.org.mx/Medicion/Paginas/PobrezaInicio.aspx> (Retrieved: May 2023).
- Curiel R. 2013. MasAgro por la seguridad alimentaria y el desarrollo agrícola sustentable de México. *Claridades Agropecuarias* 237: 9–18.
- FAO (Food and Agriculture Organization). 1999. Materiales de capacitación para la planificación agrícola. United Nations Food and Agriculture Organization. Rome, Italy. <https://www.fao.org/3/w3736s/W3736S00.htm> (Retrieved: March 2023).
- FAO (Food and Agriculture Organization). 2009. Glossary on organic agriculture. United Nations Food and Agriculture Organization. Rome, Italy. [https://www.fao.org/fileadmin/templates/organicag/files/Glossary\\_on\\_Organic\\_Agriculture.pdf](https://www.fao.org/fileadmin/templates/organicag/files/Glossary_on_Organic_Agriculture.pdf) (Retrieved: May 2023).
- FAO (Food and Agriculture Organization). 2023a. FAO terminology portal. United Nations Food and Agriculture Organization. Rome, Italy. <https://www.fao.org/faoterm/> (Retrieved: June 2023).
- FAO (Food and Agriculture Organization). 2023b. FAOSTAT. Food and agriculture data. United Nations Food and Agriculture Organization. Rome, Italy. <https://www.fao.org/faostat/en/> (Retrieved: May 2023).
- Fathonah FI, Mashilal. 2021. Rice production analysis in reflecting rice self-sufficiency in Indonesia. *E3S Web of Conference* 316: 02041. <https://doi.org/10.1051/e3sconf/202131602041>
- Fuller SW, Fellin L, Salin V. 2003. Effect of liberalized U.S.-Mexico rice trade: A spatial, multiproduct equilibrium analysis. *Agribusiness* 19 (1): 1–17. <https://doi.org/10.1002/agr.10042>
- García-Angulo JL, Hernández-Aragón L, Tavitas-Fuentes L. 2011. El Silverio: nueva variedad de arroz para el Trópico Mexicano. *Revista Mexicana de Ciencias Agrícolas* 2 (4): 607–612. <https://doi.org/10.29312/remexca.v2i4.1649>
- García-Salazar JA. 2015. Modelos de equilibrio espacial e intertemporal aplicados a la economía agrícola. *Colegio de Postgraduados: Texcoco*, México. 252 p.
- García-Salazar JA, Skaggs R. 2015. Strategies for white and yellow maize cultivar improvement research and technology transfer in Mexico. *Agronomy Journal* 107 (4): 1425–1429. <https://doi.org/10.2134/agronj14.0429>
- García-Salazar JA, Ramírez-Jaspeado R, Ávila-Soler E, Ramírez-Barraza BA. 2023. ¿Es posible disminuir la dependencia alimentaria de maíz en México? *Revista Fitotecnia Mexicana* 46 (3): 299–307.

- GlobalMap. 2021. Rutas de autotransporte carreteras de México (versión gratuita). Mapas Globales SA de CV. Ciudad de México, México. <http://www.globalmap.mx/9.html> (Retrieved: April 2021).
- Gobierno de México. 2021. Tercer informe de gobierno 2020–2021. Gobierno de México. Presidencia de la República. Ciudad de México, México. <https://www.gob.mx/presidencia> (Retrieved: March 2022).
- Hernández-Aragón L, Tavitas-Fuentes L, Álvarez-Hernández JC, Tapia-Vargas LM, Ortega-Arreola R, Esqueda-Esquivel V, Jiménez-Chong JA, López-López R. 2019. Pacífico FL 15 y Golfo FL 16, variedades multiambientales de arroz con grano extra largo para México. *Revista Mexicana de Ciencias Agrícolas* 10 (1): 23–34. <https://doi.org/10.29312/remexca.v10i1.1544>
- INEGI (Instituto Nacional de Estadística y Geografía). 2021a. Directorio nacional de unidades económicas. Instituto Nacional de Estadística y Geografía. Ciudad de México, México. <https://www.inegi.org.mx/app/mapa/denue/default.aspx> (Retrieved: March 2021).
- INEGI (Instituto Nacional de Estadística y Geografía). 2021b. Censo de población y vivienda 2020. Instituto Nacional de Estadística y Geografía. Ciudad de México, México. <https://www.inegi.org.mx/programas/ccpv/2020/> (Retrieved: March 2021).
- INIFAP (Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias). 2012. Potencial productivo de especies agrícolas de importancia socioeconómica en México. Ciudad de México, México. 140 p.
- Ireta-Paredes AR, Altamirano-Cárdenas JR, Ayala-Garay AV, Covarrubias-Gutiérrez I. 2015. Análisis macroeconómico y microeconómico de la competitividad de arroz en México. *Agricultura Sociedad y Desarrollo* 12 (4): 499–514. <https://doi.org/10.22231/asyd.v12i4.242>
- Mendoza-Mondragón R. 2022. Estimado de procesamiento por estado 2020. Especialista en agroindustria del arroz en México. Texcoco, México.
- Moctezuma-López G, Pérez-Miranda R, González-Hernández A, Ramírez Sánchez EU. 2021. Tecnología de potencial productivo de arroz (*Oryza sativa* L.) en el Estado de Tabasco, México y su aportación a la soberanía alimentaria. *Revista Chapingo Serie Agricultura Tropical* 1 (2): 9–23. <https://doi.org/10.5154/r.rchsagt.2021.02.02>
- Otero G, Pechlaner G, Can GE. 2013. The political economy of “food security” and trade: Uneven and combined dependency. *Rural Sociology* 78 (3): 263–289. <https://doi.org/10.1111/ruso.12011>
- Ray DK, Mueller ND, West PC, Foley JA. 2013. Yield trends are insufficient to double global crop production by 2050. *PLoS ONE* 8 (6): e66428. <https://doi.org/10.1371/journal.pone.0066428>
- SADER (Secretaría de Agricultura y Desarrollo Rural). 2019. ¿A que nos referimos con autosuficiencia alimentaria? Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Ciudad de México, México. <https://www.gob.mx/agricultura/es/articulos/a-que-nos-referimos-con-autosuficiencia-alimentaria?idiom=es> (Retrieved: February 2023).
- SAGARPA (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación). 2017. Planeación Agrícola Nacional 2017–2030. Arroz Mexicano. Gobierno de México. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Ciudad de México, México. 20 p.
- Salin V, Williams G, Haigh M, Malaga J, Madriñán JC, Sheaff K. 2000. Structure of the Mexican rice industry: Implications for strategic planning. International market research report No. IM 2-00. Texas Agricultural Market Research Center. College Station, TX, USA. 66 p.

- SIAP (Servicio de Información Agroalimentaria y Pesquera). 2021. Volumen y valor importado y exportado de arroz por fracción arancelaria, país origen-destino y aduana de entrada-salida 2020. Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Servicio de Información Agroalimentaria y Pesquera. Ciudad de México, México. <https://ventanillaunica.gob.mx/vucem/Clasificador.html> (Retrieved: May 2023).
- SIAP (Servicio de Información Agroalimentaria y Pesquera). 2022a. Panorama Agroalimentario 2022. Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Servicio de Información Agroalimentaria y Pesquera. Ciudad de México, México. <https://www.gob.mx/siap/prensa/panorama-agroalimentario-2022?idiom=es> (Retrieved: May 2023).
- SIAP (Servicio de Información Agroalimentaria y Pesquera). 2022b. Sistema de información agroalimentaria de consulta SIACON 2022. Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Servicio de Información Agroalimentaria y Pesquera. Ciudad de México, México. <https://www.gob.mx/siap/documentos/siacon-ng-161430> (Retrieved: May 2023).
- SIAP (Servicio de Información Agroalimentaria y Pesquera). 2023. Frontera agrícola. Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Servicio de Información Agroalimentaria y Pesquera. Ciudad de México, México. <https://cmgs.gob.mx/siapdsg/apps/webappviewer/index.html?id=19e91e718f7644c380c178703e46f1ef> (Retrieved: February 2023).
- Schwentesius RR, Gómez-Cruz MA. 1999. Ajuste y cambio estructural en la agricultura mexicana. El caso del arroz. Universidad Autónoma Chapingo: Chapingo, México. 50 p.
- Takayama T, Judge GG. 1971. Spatial and temporal price and allocation models. North Holland: Amsterdam, Netherlands. 528 p.
- Torres TF, Rojas MA. 2018. Suelo agrícola en México: retrospectiva y prospectiva para la seguridad alimentaria. *Realidad, Datos y Espacio Revista Internacional de Estadística y Geografía* 9 (3): 137–155.
- Turrent-Fernández A, Camas-Gómez R, López-Luna A, Cantú-Almaguer M; Ramírez-Silva J, Medina-Méndez J, Palafox-Caballero A. 2004. Producción de maíz bajo riego en el sureste de México: I. Análisis agronómico. *Agricultura Técnica en México* 30 (2): 153–167.
- Twine EE. 2023. Implications of the ban on rice cultivation in Uganda's wetlands for breeding and seed systems programming. *Market Intelligence BriefSeries* 4. CGIAR: Montpellier, France. 5 p.
- Vázquez-Alvarado JMP, Martínez-Damián MA. 2015. Estimación empírica de elasticidades de oferta y demanda. *Revista Mexicana de Ciencias Agrícolas* 6: 955–965. <https://doi.org/10.29312/remexca.v6i5.590>

## TEMPERATURE AND PRECIPITATION TRENDS DUE TO CLIMATE CHANGE IN THE HUIXTLA RIVER BASIN IN CHIAPAS, MEXICO

Ricardo Álvarez-López<sup>1</sup>, Laura Alicia Ibáñez-Castillo<sup>1\*</sup>,  
Mario Alberto Vázquez-Peña<sup>1</sup>, Agustín Ruíz-García<sup>1</sup>

<sup>1</sup>Universidad Autónoma Chapingo. Posgrado en Ingeniería Agrícola y Uso Integral del Agua. Carretera México-Texcoco km 36.5, Chapingo, State of Mexico, Mexico. C.P. 56230.

\* Author for correspondence: libacas@gmail.com

### ABSTRACT

The objective of this work was to analyze whether there is a trend in climate change in the Huixtla River basin on the Mexican Pacific coast in the State of Chiapas. To detect this, temperature and precipitation trends were analyzed using data for the 1960–2014 period and the 27 indices proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI) at Des poblado, Escuintla, Finca Chicharras, Huehuetán, Huixtla, and Motozintla weather stations of the National Meteorological Service (SMN). Missing data were collected where necessary for precipitation using the U.S. National Weather Service method and for temperatures using the Climate Engine platform. The indices were obtained with RCLimDex by conducting the proposed data quality controls and classified on the basis of their statistical significance (0.05) and their increasing or decreasing trend. Among the changes found, higher temperatures were detected in the middle and lower western parts of the basin (TX90p), as well as a longer period of hot days (WSDI). The upper and lower eastern parts of the basin presented a shorter period of hot days. The upper and lower parts of the basin showed a cooling trend, with colder days (TX10p) over longer periods (CSDI). Across the basin, precipitation has increased by one and five days (RX1day and RX5day) as well as in total amount (PRCPTOT). In general, there were shorter dry periods (CDD) and longer wet periods (CWD). Rainfall above the R5mm, R10mm, R20mm, R70mm, and R150mm thresholds across the basin showed an increasing trend.

**Keywords:** indices, ETCCDI, RCLimDex.

### INTRODUCTION

The World Meteorological Organization (WMO, 2022) defines climate change as a statistically significant variation in the average state of climate or its variability occurring continuously over a long period of time, spanning at least three decades. In this regard, the Intergovernmental Panel on Climate Change mentions change detection as the act of addressing the question of whether the climate has a statistically demonstrable change. The causes of observed changes in a natural system affected

**Citation:** Álvarez-López R, Ibáñez-Castillo LA, Vázquez-Peña MA, Ruíz-García A. 2024. Temperature and precipitation trends due to climate change in the Huixtla river basin in Chiapas, Mexico. *Agrociencia* 58(5): 627-640. <https://doi.org/10.47163/agrociencia.v58i5.3087>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: October 11, 2023.

Approved: April 23, 2024.

**Published in Agrociencia:**  
July 10, 2024.

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



by climate must be established following a set of consistent methods (IPCC, 2014). These statistically measured methods link human-induced changes in climate to a deterioration in human health, plant and animal life, and marine processes.

In its sixth synthesis report, the IPCC (2023) mentions examples of key risks in different regions, with a medium confidence level, in the Central and South American region, including the risk to water security, severe impacts on human health, degradation of coral reefs, food security risk from extreme droughts, and damage to structures from natural disasters. This report also mentions that systemic barriers, such as missing information on finance and practices, including the absence of climate knowledge and data, hinder progress on adaptation.

In an attempt to answer questions about climate extremes affecting human and natural systems, indices are used that attempt to extract information from daily data, weather observations, and objectively (Zhang *et al.*, 2011). These indices are proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI) as defined by Frich *et al.* (2002) and are based on the European Climate Assessment (ECA) indices (Klein Tank *et al.*, 2002) for analyzing climate trends during the second half of the 20th century. A total of 27 indices were defined.

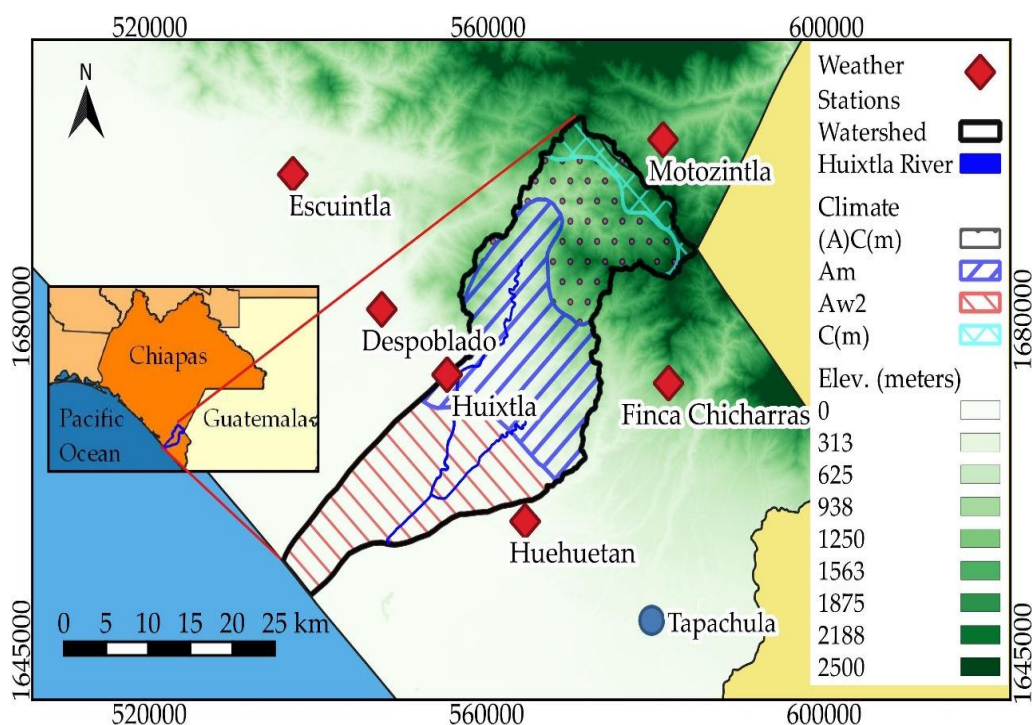
In Mexico, the ETCCDI indices have been used in several studies, both for temperature and precipitation. Among them, Ortiz-Gómez *et al.* (2020) calculated 10 precipitation indices for the state of Zacatecas for the 1961–2014 period. Ruiz-Álvarez *et al.* (2020) obtained 11 precipitation-related indices for the entire state of Aguascalientes for the 1980–2013 period. Colorado-Ruiz and Cavazos (2021) focused on 15 precipitation frequency and intensity indices, of which eight are part of the ETCCDI list, to evaluate extreme and non-extreme daily precipitation trends for Mexico and the southern United States from 1981 to 2010.

Since 2005, on the coast of the State of Chiapas, Mexico, maximum 24-hour rainfall values and increased instantaneous flows have been observed in several watersheds in the area (Pérez-Nieto *et al.*, 2012), with the worst effects registered in the Huixtla watershed. Moreover, the Chiapas coast features an area known as the “coffee route,” which is particularly vulnerable to variations in temperature and precipitation considering that diseases such as coffee rust can intensify (Libert-Amico and Paz-Pellat, 2018).

Research carried out in the State of Chiapas concerning the use of indices for the detection of climate change trends includes the work of de la Mora-Orozco *et al.* (2016), where they analyzed data from 16 stations for the 1960–2009 period for eight indicators based on maximum and minimum temperatures and precipitation. Similarly, Figueroa-Gallegos (2016) conducted research at two meteorological stations located in the Sabinal River basin, Chiapas. It is necessary to expand research in different hydrological regions. The objective of this study was to obtain the ETCCDI climate change indices related to temperature and precipitation for the Huixtla River basin located on the coast of Chiapas and analyze their trends.

## MATERIALS AND METHODS

The study area is located within hydrological region No. 23, “Costa de Chiapas,” defined by the Huixtla River basin and classified as RH23, Chiapas, by the National Water Commission (CONAGUA). In this region, only meteorological station 7077 Huixtla is located within the Huixtla River basin; the other stations used for the study are located surrounding the basin: 7038 Despoblado, 7053 Escuintla, 7057 Finca Chicharras, 7075 Huehuetán, and 7119 Motozintla of the National Meteorological Service (SMN) (Figure 1). The Huixtla River basin has an area of 828.97 km<sup>2</sup> and presents a sharp variation in altitude, ranging from 0 to 2500 m (Figure 1).



**Figure 1.** Location of the basin under study, the meteorological stations analyzed, their climatic classification, georeferencing, and altitude in the state of Chiapas, Mexico.

### Climate and land use of the basin

The predominant climates in the basin under study (Figure 1) are warm sub-humid with summer rainfall (Aw2), warm humid with summer rainfall (Am), semi-warm humid with summer rainfall ((A)C(m)), and temperate humid with summer rainfall (C(m)) (García, 2001). It is important to note that several stations are also located in the Huehuetán River and the Despoblado River basins, which results in a larger area of analysis by having to use data from weather stations in neighboring basins.

According to the cartography Series VII of Land Use and Vegetation Scale 1:250 000 (INEGI, 2021), the main land uses and vegetation in the basin are permanent and semi-permanent rainfed agriculture, cultivated pasture, mangrove, and *tular* in the middle and lower parts of the basin, and mesophilic mountain forest, secondary arboreal, and shrubby vegetation of pine, pine-oak, and oak-pine forest in the upper part of the basin. The Chiapas coffee route is set through some of these analyzed weather stations. According to the Local Climatic Effects Chart Scale 1:250 000 (INEGI, 1984), in the period from May to October, the total rainfall in the basin ranges from 1700 to 3000 mm, with the highest rainfall in the middle part of the basin. From November to April, the annual rainfall varies from 125 mm at low elevations to 700 mm at mid-high elevations. The average maximum temperatures for most of the year range from 21 to 33 °C. Average minimum temperatures range from 12 to 21 °C in the period from May to October and from 9 to 18 °C in the period from November to April.

#### **Weather stations**

The stations were selected on the basis of their proximity to the basin under study and the length of the temperature and precipitation data records (more than 30 years), with no more than 20 % missing data (SMN, 2023). The periods of analysis were set in relation to the maximum record of each station and were defined as follows: 1965–2014 for Despoblado station, 1960–2014 for Escuintla station, 1961–2013 for Finca Chicharras station, 1965–2014 for Huehuetán station, 1961–2014 for Huixtla station, and 1960–2014 for Motozintla station. More recent years were not analyzed due to incomplete data.

#### **Generation of missing data**

Daily data series for minimum and maximum temperatures and precipitation were obtained from the National Weather Service website (SMN, 2023). These data series presented missing data for all variables on different days and years. Missing data for maximum and minimum temperatures from 1980 onwards were generated using the Climate Engine platform (<https://www.climateengine.org/>) for each weather station; for years prior to 1980, the U.S. National Weather Service (WS) method was used (Campos-Aranda, 1998). For missing precipitation data, the WS method was also used.

#### **Data analysis and quality control**

Data preparation and calculation of the 27 ETCCDI indicators was carried out as recommended in the user manual of the RClmDex software (Zhang *et al.*, 2018). Four additional user-defined parameters were also included in the analysis (frost days, summer days, ice days, and tropical night days), making a total of 31 indices (Table 1). Basic and extra data quality control was performed with the component included in the RClmDex (Zhang *et al.*, 2018). Quality control consists of identifying values inconsistent with the series or outliers, such as negative precipitation amounts, very high precipitation, rounding conditions, and data repeated on a certain number of

**Table 1.** List of Expert Team on Climate Change Detection and Indices (ETCCDI) indices (Zhang *et al.*, 2018).

Identification	Indicator	Definition	Unit
FD0	Frost days	Number of days in a year when daily minimum temperature (TN) < 0 °C.	Days
CDD	Consecutive dry days	Maximum number of consecutive days with daily precipitation (RR) < 1 mm.	Days
CSDI	Cold spell duration index	Annual count of days with at least 6 consecutive days in which TN < 10th percentile.	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm.	Days
DTR	Daytime temperature range	Average monthly difference between daily maximum temperature (TX) and TN.	°C
GSL	Growing season length	Annual counts between the first period of at least 6 days with daily mean temperature (TG) > 5 °C and first period (after July 1st) of 6 days with TG < 5 °C.	Days
ID0	Ice days	Number of days in a year when TX (daily maximum) < 0 °C.	Days
PRCPTOT	Total precipitation	Total annual precipitation on wet days (RR ≥ 1 mm).	mm
R10	Number of days with heavy precipitation	Number of days in a year when precipitation (PCP) ≥ 10 mm.	Days
R20	Number of days with very heavy precipitation	Number of days in a year when PCP ≥ 20 mm.	Days
R95p	Very wet days	Total annual precipitation where RR > 95th percentile.	Mm
R99p	Extremely wet days	Total annual precipitation where RR > 99th percentile.	mm
Rnn	Number of days with rain over nn mm	Number of days in a year when PCP ≥ nn mm; nn is a user-defined parameter.	Days
RX1day	Wettest day	Maximum RR during the period of interest.	mm
RX5day	Wettest 5-day period	Maximum 5-day accumulated RR during the period of interest.	mm
SDII	Simple daily intensity index	Total annual rainfall divided by the number of wet days (defined by PCP ≥ 1.0 mm) in a year.	mm day <sup>-1</sup>
SU25	Summer days	Number of days in a year when TX (daily maximum) > 25 °C.	Days
TN10p	Cold nights	Percentage of days when TN < 10th percentile.	Days
TN90p	Hot nights	Percentage of days when TN > 90th percentile.	Days
TNn	Min Tmin	Monthly minimum value of TN.	°C
TNx	Max Tmin	Monthly maximum value of TN.	°C
TR20	Tropical nights	Number of days in a year when TN > 20 °C.	Days
TX10p	Cold days	Percentage of days when TX < 10th percentile.	Days
TX90p	Hot days	Percentage of days when TX > 90th percentile.	Days
TXn	Min Tmax	Monthly minimum value of TX.	°C
TXx	Max Tmax	Monthly maximum value of TX.	°C
WSDI	Warm spell duration index	Annual count of days with at least 6 consecutive days when TX > 90th percentile.	Days

days continuously (Jaimes-Rodríguez *et al.*, 2022). Homogeneity analyses were performed with the RHtests V4 module (Wang and Feng, 2013a), which performs a Maximum Penalty F-Test for maximum and minimum temperatures, and with the RHtests\_flyPrcp module (Wang and Feng, 2013b) for precipitation, which performs the transPMFred algorithm also based on the Maximum Penalty F-Test. Homogenization of the data series was also performed with quantile adjustment (Wang *et al.*, 2010) when the series were not homogeneous.

### Index trend

To determine the degree of change or trends in the calculated indices and their statistical significance, the system proposed by Ruiz-García *et al.* (2021) of using signs and colors was used. In addition, a sign was associated with the degree of decrease or increase (- and +, respectively), ranging from low to very high, according to the slope of the line of adjustment (Table 2). A color was assigned in the case of a statistically significant difference (0.05). Indices that did not present statistically significant relevance were left without color. This process was performed by a module included in RCLimDex (Zhang *et al.*, 2018).

**Table 2.** Rating system for the slope of the line and statistically significant significance of the index.

Tendency	Range	Sign and color*	Range	Sign and color*
Low	-0.01 to -0.05	-	0.01 to 0.05	+
Moderate	-0.05 to -0.1	--	0.05 to 0.1	++
High	-0.1 to -0.5	---	0.01 to 0.5	+++
Very high	< -0.5	----	> 0.5	++++

\*If not statistically significant, the color is omitted.

## RESULTS AND DISCUSSION

Regarding the temperature indices (Table 3), Escuintla and Despoblado stations had the most indices (seven) with a statistically significant tendency to increase, followed by Chicharras with six. Motozintla had the most significantly decreasing indices, with 11, followed by Huehuetán, which had seven. Finally, Huixtla had five significant index increases.

For temperature indices, the Escuintla and Chicharras stations showed significant increases in the summer days index (SU25), with rates of 1.43 and 13.07 days per decade, respectively. This is consistent with the findings of de la Mora-Orozco *et al.* (2016), who found that most stations had an increasing trend in this index, but with marked oscillations. This is also in agreement with Zarazúa-Villaseñor *et al.* (2014), although with a slight increase and little impact in the Southern Gulf coastal plains.

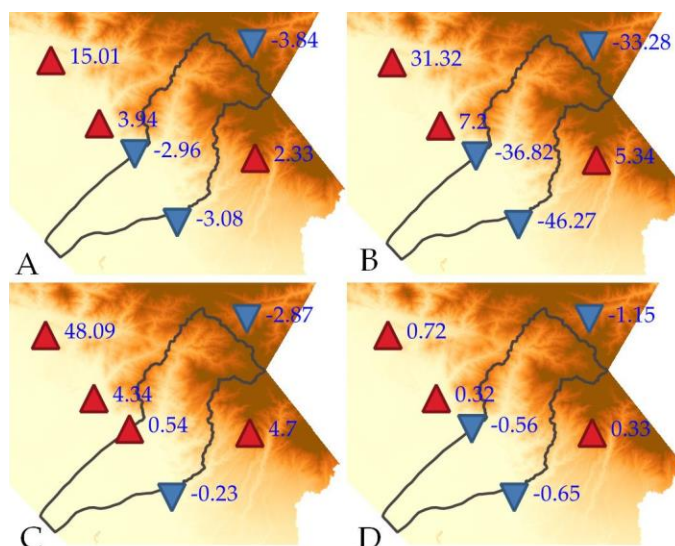
**Table 3.** Temperature indices for the weather stations analyzed in Chiapas, Mexico.

Index	Despoblado	Escuintla	Chicharras	Huehuetán	Huixtla	Motozintla
Latitude (°)	15.203	15.331	15.133	15.002	15.141	15.364
Length (°)	-92.558	-92.656	-92.242	-92.400	-92.486	-92.248
Altitude (m)	63	92	1328	65	40	1260
SU25	-	+++	++++	-	-	----
ID0	ND	ND	ND	ND	ND	ND
TR20	+++	++++	+	---	----	----
FD0	ND	ND	ND	ND	ND	ND
SUnn*	++++	++++	++++	----	----	----
TRnn*	-	++	++	----	--	----
GSL	+	-	+	+	-	-
TXx	+	+	+	--	--	----
TXn	+	+++	+	+	+	----
TNx	-	-	-	--	-	--
TNn	+	+	-	-	+	----
TX10p	--	---	---	++++	++++	++++
TX90p	+++	++++	+++	---	---	---
TN10p	---	-	+++	++++	+++	++++
TN90p	++++	+	-	---	+++	----
WSDI	++++	++++	+++	-	++	----
CSDI	++	+++	++++	++++	++++	++++
DTR	+	++	-	-	-	-

\*The abbreviations nn refer to temperature thresholds for the stations Despoblado, Escuintla, Huehuetán, and Huixtla established at 35 °C. Chicharras and Motozintla stations have a threshold established at 28 °C. ND: no index result.

The frequency of hot days (TX90p) showed an increasing trend from high to very high significance, with values of 3.94, 2.33, and 15.01 days per decade for Despoblado, Chicharras, and Escuintla, respectively (Figure 2A). At the same stations, the SU35 index changed at a very high rate of 7.20, 31.31, and 5.34 days per decade, respectively (Figure 2B). The WSDI shifted from very high to high by 4.34, 48.09, and 4.09 days per decade (Figure 2C). For SU25, TX90p, SUnn, and WSDI indices at Huehuetán, Huixtla, and Motozintla, there were decreasing trends from high to very high, especially in Motozintla, with values for the SUnn index of 46.27, 36.82, and 33.38 days per decade (Figure 2B), and for the TX90p index of 3.08, 2.26, and 3.84 days per decade (Figure 2A). This was also seen in the SU25 and WSDI indices, but with slower rates of decline (Figure 2C).

Hot-day behavior varied across the stations analyzed. Zarazúa-Villaseñor *et al.* (2014) found a general trend of increase in the Southern Gulf Coastal Plains, a region near the sea. Given the variability in the length of hot days, it is possible to conclude that the middle and lower western parts of the basin had more days with higher temperatures



**Figure 2.** Temperature index trends and rates of change. A: TX90p; B: SUnn; C: WSDI; D: TXx.  $\Delta$ : increase;  $\nabla$ : decrease.

(35 and 28 °C) and a longer period of hot days, whereas the upper and lower eastern parts of the basin had a shorter period of hot days and fewer days above the 28 °C threshold.

For the extreme maximum temperature (TXx) index, de la Mora-Orozco *et al.* (2016) reported a clear trend of increase in the State of Chiapas, with 10 out of 16 stations showing an increase; however, the stations they studied were not the same as the ones presented here. In this study, three stations had low increases (Despoblado, Escuintla, and Chicharras), while three had moderate to high decreases (Huehuetán, Huixtla, and Motozintla) (Figure 2D). This can be interpreted as a slight increase in extreme maximum temperatures from the center to the west of the basin, as well as a decrease in extreme maximum temperatures in the upper and lower basin.

For the frequency of cool days (TX10p), Huehuetán, Huixtla, and Motozintla showed a very high tendency of significant increase, with values of 6.62, 7.00, and 12.02 days per decade, in contrast to what was found in Despoblado, Escuintla, and Chicharras, which showed a moderate to high decrease at rates of 0.64, 3.37, and 1.5 days per decade. Similarly, the TN10p index, which measures the frequency of cool nights, increased significantly from high to very high in Huehuetán, Huixtla, Motozintla, and Chicharras (6.51, 2.92, 7.67, and 4.67 days per decade, respectively). However, the same TN10p index in Despoblado and Escuintla showed no significant decreasing trend. Zarazúa-Villaseñor *et al.* (2014) found a decreasing trend in most of the stations analyzed in the Southern Gulf Coastal Plains area, which contradicts the current frequency of cool nights.

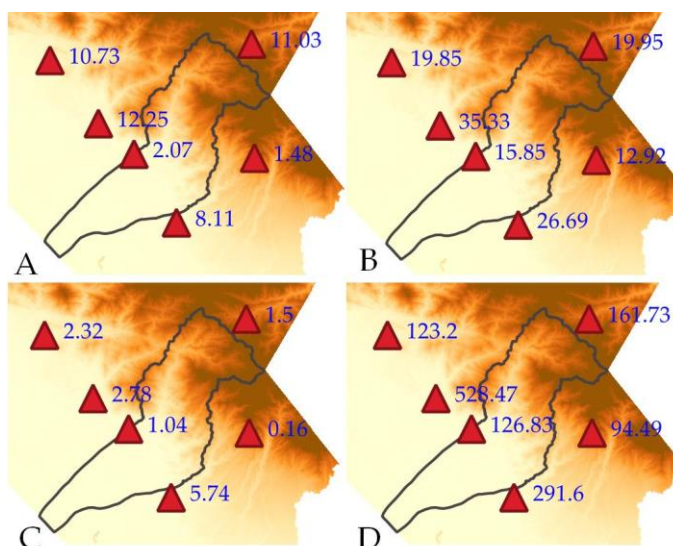
The CSDI index or duration of the cold period increased in all stations, with values of 9.85, 17.1, 13.92, and 12.5 days per decade at Chicharras, Huehuetán, Huixtla, and Motozintla, respectively, but no significant increases in Despoblado or Escuintla. This is consistent with the behavior of the upper and lower parts of the basin, in this case with more cool days and for longer periods of time, with the latter being more generalized throughout the basin. In the middle of the basin, there was no apparent trend.

In terms of precipitation, Despoblado station had the most significant rates of change, with 12 indices overall, 10 increasing and two decreasing. This was followed by Escuintla and Motozintla, both with 10 indices, nine of which are increasing and one decreasing. Chicharras had the fewest significant trend indices (four), with three increasing and one decreasing (Table 4).

**Table 4.** Precipitation indices for the weather stations analyzed in Chiapas, Mexico.

Indices	Despoblado	Escuintla	Chicharras	Huehuetán	Huixtla	Motozintla
Latitude (degrees)	15.203	15.331	15.133	15.002	15.141	15.364
Length (degrees)	-92.558	-92.656	-92.242	-92.400	-92.486	-92.248
Elev. (msnm)	63	92	1328	65	40	1260
RX1day	++++	++++	+++	++++	+++	++++
RX5day	++++	++++	++++	++++	++++	++++
SDII	--	-	++	---	-	+
CDD	---	---	+++	---	---	---
CWD	+++	+++	+	++++	+++	+++
R95p	++++	++++	++++	++++	++++	++++
R99p	++++	++++	++++	++++	++++	++++
PRCPTOT	++++	++++	++++	++++	++++	++++
R0.1mm	---	-	---	++++	---	---
R5mm	++++	+++	-	++++	+++	++++
R10mm	++++	+++	+++	++++	+++	++++
R20mm	++++	+++	+++	+++	+++	+++
R70mm	+++	+	+++	+	+	+
R150mm	+	+	+	+	+	+

The RX1day and RX5day indices showed a general trend of increasing in all stations. For RX1day, there were very high significant increase rates in Despoblado, Escuintla, and Motozintla (12.25, 10.73, and 11.03 mm per decade, respectively) (Figure 3A), while the rest of the stations showed very high and high non-significant increase trends. Except for Chicharras, RX5day increased significantly at rates of 35.33, 19.85, 26.69, 15.85, and 19.95 mm per decade in Despoblado, Escuintla, Huehuetán, Huixtla, and Motozintla.



**Figure 3.** Precipitation trends and rates of change. A: RX1day; B: RX5day; C: CWD; D: PRCPTOT.  $\Delta$ : increase.

The maximum precipitation in each month, over the course of one and five days, has increased throughout the basin, with the year 2005 highlighting the months of September and October, which experienced high precipitation in previous years. The SDII index showed only a moderately significant increase in Chicharras (0.93 mm day<sup>-1</sup> per decade) and a highly significant decrease in Huehuetán (1.65 mm day<sup>-1</sup> per decade).

For the maximum dry period duration, or CDD index, a significant, very high decrease trend was presented in most stations (4 out of 6), with rates of 19.35 days per decade in Despoblado, 5.51 days per decade in Escuintla, 16.99 days per decade in Huehuetán, and 20.92 days per decade in Motozintla, indicating dry periods of shorter duration in the basin. This is somewhat consistent with de la Mora-Orozco *et al.* (2016), who found a slight decreasing trend in CDD but no significant trend across the entire State of Chiapas.

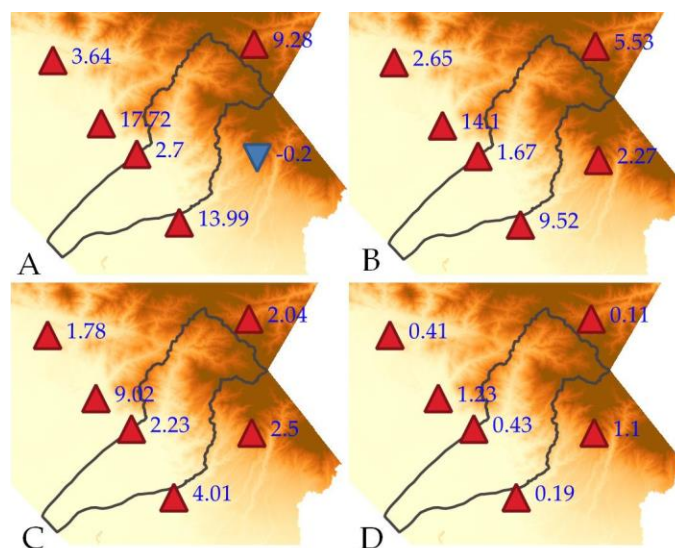
There was a significant increase in the maximum duration of the wet period, or CWD (Figure 3C), with changes of 2.78 days per decade in Despoblado, 2.32 days per decade in Escuintla, 5.74 days per decade in Huehuetán, and 1.5 days per decade in Motozintla. The basin experienced both shorter dry periods and longer wet periods. This incremental behavior is consistent with Wootton *et al.* (2023), who found that the average length of the wet period in the Sierra Madre de Chiapas zone increased by  $2.7 \pm 13.6$  days in the 1990–2016 period. Additionally, the wet season began earlier in lower-elevation zones.

The R95p and R99p indices showed a generalized tendency for a very high increase. R95p increased at very high rates across the stations, with values of 112.04 mm per

decade in Despoblado, 62.59 mm per decade in Escuintla, 106.7 mm per decade in Chicharras, and 55.24 mm per decade in Motozintla, but no significant increases in Huehuetán or Huixtla. R99p rates were lower than R95p but still quite high, with significant rates of 41.2 mm per decade in Despoblado, 44.75 mm per decade in Escuintla, and 19.47 mm per decade in Motozintla; however, rates at Chicharras, Huehuetán, and Huixtla were not significant.

In all of the stations analyzed, a very high increase trend was observed for the total precipitation index of wet days, or PRCPTOT (Figure 3D), which was not significant in the Chicharras station but increased at a very high rate of 94.49 mm per decade. In the remaining stations, there were statistically significant increases, with values of 528.47 mm per decade in Despoblado, 123.2 mm per decade in Escuintla, and 291.6 mm per decade in Huehuetán. This trend of increasing precipitation was consistent with what Wootton *et al.* (2023) found in their analysis of trends on the Chiapas coast, which showed increases in precipitation in June and September. As a result, total annual wet-day precipitation increased at a rapid rate across the basin, particularly along the coast.

For the annual total of days with a defined precipitation threshold (Rnmm) of 0.1, 5, 10, 20, 70, and 150 mm, the following was observed: for R0.1mm, there was no clear general trend of increase or decrease; for R5mm, there was a trend of increase in most stations from very high to high (significant in five stations), with Despoblado station having the highest rate of increase with 17.72 days per decade (Figure 4A). At R10mm (Figure 4B) and R20mm (Figure 4C), there was a similar pattern of significant increases ranging from very high to high, with Despoblado once again having the highest rate of 14.1 days per decade. The R70mm index showed a significant trend of increasing



**Figure 4.** Trends and rates of change of Rnmm indices with defined precipitation thresholds. A: R5mm; B: R10mm; C: R20mm; D: R70mm.  $\Delta$ : increase;  $\nabla$ : decrease.

from low to high at three stations, but at a slower rate than the lower rainfall Rnnmm indices; Despoblado had the highest rate at 1.23 days per decade, and Motozintla had the lowest at 0.11 days per decade (Figure 4D). Finally, in the R150mm index, there was a tendency to increase less than the R70mm, but only in Escuintla, with 0.2 days per decade.

From the behavior of the Rnnmm indices, it can be mentioned that there was a general trend of increase from very high to high in the occurrence of rainfall above the defined thresholds. The rate of change of these indices decreased when analyzing rainfall of greater magnitude, with the lowest rate in R150mm. This coincides with the occurrence of each event (0.1, 5, 10, 20, 70, and 150 mm) of rainfall during a year.

In general, these temperature and precipitation tendencies are more noticeable in the lower and upper parts, either due to their proximity to the sea or the dry zone on the Grijalva side; however, according to basin surveys, the middle parts have a good vegetation cover that has changed little over time. Although previous climate change studies have focused on the large Grijalva basin, it is the only available information on the State of Chiapas, as the Grijalva is where hydroelectric plants are located and thus the most studied area, leaving the Chiapas coastal hydrological region, which has high rainfall, water flow, and deforestation but no hydroelectric plants or storage dams (even of medium size), somewhat forgotten. On the other hand, when national studies are contracted to a single entity, accuracy suffers due to the number of weather stations considered and/or the inability to detail missing rainfall and temperature data.

## CONCLUSIONS

Temperature changes in the Huixtla River basin are reflected in daily maximum threshold indices of 35 and 28 °C for the time period under consideration. Stations in the middle altitudes of the basin tend to raise their threshold to 28 °C, while those in lower or higher altitudes tend to lower their maximum threshold to 35 °C. Precipitation has also changed; most of the rainfall indices showed increasing trends, notably those related to daily (RX1day), 5-day (RX5day), and total annual wet days (PRCTOT). This results in increased rainfall across the basin and a longer wet period (CWD). These changes in precipitation are concentrated in daily rainfall greater than 5, 10, 20, and 70 mm per day.

## REFERENCES

- Campos-Aranda FD. 1998. Procesos del ciclo hidrológico. Universidad Autónoma de San Luis Potosí: San Luis Potosí, México. 529 p.
- Colorado-Ruiz G, Cavazos T. 2021. Trends of daily extreme and non-extreme rainfall indices and intercomparison with different gridded data sets over Mexico and the southern United States. *International Journal of Climatology* 41 (11): 5406–5430. <https://doi.org/10.1002/joc.7225>

- de la Mora-Orozco C, Ruíz-Corral JA, Flores-López HE, Zarazúa-Villaseñor P, Ramírez-Ojeda G, Medina-García G, Rodríguez-Moreno VM, Chávez-Durán ÁA. 2016. Índices de cambio climático en el estado de Chiapas, México, en el periodo 1960–2009. *Revista Mexicana de Ciencias Agrícolas* 13: 2523–2534.
- Figuroa-Gallegos JA. 2016. Índices de cambio climático en la cuenca del río Sabinal, Chiapas, México. *Aqua-LAC* 8 (2): 36–41. <https://doi.org/10.29104/phi-aqualac/2016-v8-2-04>
- Frich P, Alexander L, Della-Marta P, Gleason B, Haylock M, Klein Tank A, Peterson T. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* 19: 193–212. <https://doi.org/10.3354/cr019193>
- García E. 2001. *Climas. Catálogo de metadatos geográficos*. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad: Ciudad de México, México. <http://geoportal.conabio.gob.mx/metadatos/doc/html/clima1mgw.html> (Retrieved: May 2023).
- INEGI (Instituto Nacional de Estadística y Geografía). 1984. Conjunto de datos vectoriales del Continuo Nacional [Map]. Instituto Nacional de Estadística y Geografía. Ciudad de México, México. <https://www.inegi.org.mx/temas/climatologia/> (Retrieved: June 2023).
- INEGI (Instituto Nacional de Estadística y Geografía). 2021. Conjunto de datos vectoriales del uso de suelo y vegetación [Map]. Instituto Nacional de Estadística y Geografía. Ciudad de México, México. <http://geoportal.conabio.gob.mx/metadatos/doc/html/usv250s7gw.html> (Retrieved: June 2023).
- IPCC (Intergovernmental Panel on Climate Change). 2014. *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland. 151 p.
- IPCC (Intergovernmental Panel on Climate Change). 2023. *Climate Change 2023: Synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland. <https://doi.org/10.59327/ipcc/ar6-9789291691647>
- Jaimes-Rodríguez J, Ibáñez-Castillo LA, Arévalo-Galarza GA, Vázquez-Peña MA, Monterroso-Rivas AI. 2022. Tendencias en la precipitación diaria de la cuenca alta Laja-Peñuelitas, Guanajuato. *Revista Mexicana de Ciencias Agrícolas* 12 (7): 1263–1274. <https://doi.org/10.29312/remexca.v12i7.2919>
- Klein Tank AMG, Wijngaard JB, Können GP, Böhm R, Demarée G, Gocheva A, Mileta M, Pashiardis S, Hejkrlik L, Kern-Hansen C *et al.* 2002. Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *International Journal of Climatology* 22 (12): 1441–1453. <https://doi.org/10.1002/joc.773>
- Libert-Amico A, Paz-Pellat F. 2018. Del papel a la acción en la mitigación y adaptación al cambio climático: la roya del café en Chiapas. *Madera y Bosques* 24. <https://doi.org/10.21829/myb.2018.2401914>
- Ortiz-Gómez R, Muro-Hernández LJ, Flowers-Cano RS. 2020. Assessment of extreme precipitation through climate change indices in Zacatecas, Mexico. *Theoretical and Applied Climatology* 141 (3): 1541–1557. <https://doi.org/10.1007/s00704-020-03293-2>
- Pérez-Nieto S, Arellano-Monterrosas JL, Ibáñez-Castillo LA, Hernández-Saucedo FR. 2012. Estimación de la erosión hídrica provocada por el huracán Stan en las cuencas costeras de Chiapas, México. *Terra Latinoamericana* 30 (2): 103–110.
- Ruiz-Álvarez O, Singh VP, Enciso-Medina J, Ontiveros-Capurata RE, dos Santos CAC. 2020. Observed trends in daily extreme precipitation indices in Aguascalientes, Mexico. *Meteorological Applications* 27 (1): e1838. <https://doi.org/10.1002/met.1838>

- Ruiz-García P, Conde-Álvarez C, Gómez-Díaz JD, Monterroso-Rivas AI. 2021. Projections of local knowledge-based adaptation strategies of Mexican coffee farmers. *Climate* 9 (4): 60. <https://doi.org/10.3390/cli9040060>
- SMN (Servicio Meteorológico Nacional). Climatología diaria 2023. Gobierno de México. Comisión Nacional del Agua. Servicio Meteorológico Nacional. Ciudad de México, México. <https://smn.conagua.gob.mx/es/> (Retrieved: September 2023).
- Wang XL, Feng Y. 2013a. RHtests V4 user manual. Climate Research Division. Atmospheric Science and Technology Directorate. Science and Technology Branch, Environment Canada. Toronto, Canada. <http://etccdi.pacificclimate.org/software.shtml> (Retrieved: May 2023).
- Wang XL, Feng Y. 2013b. RHtests\_dlyPrpc user manual. Climate Research Division. Atmospheric Science and Technology Directorate. Science and Technology Branch, Environment Canada. Toronto, Canada. <http://etccdi.pacificclimate.org/software.shtml> (Retrieved: May 2023).
- Wang XL, Chen H, Wu Y, Feng Y, Pu Q. 2010. New techniques for the detection and adjustment of shifts in daily precipitation data series. *Journal of Applied Meteorology and Climatology* 49 (12): 2416–2436. <https://doi.org/10.1175/2010JAMC2376.1>
- WMO (World Meteorological Organization). 2022. FAQs—Climate. World Meteorological Organization. Geneva, Switzerland. <https://public.wmo.int/en/about-us/frequently-asked-questions/climate> (Retrieved: May 2023).
- Wootton A, Enríquez PL, Navarrete-Gutiérrez D. 2023. Regional patterns of vegetation, temperature, and rainfall trends in the coastal mountain range of Chiapas, Mexico. *Atmósfera* 36 (1): 91–122. <https://doi.org/10.20937/atm.53026>
- Zarazúa-Villaseñor P, Ruiz-Corral JA, Ramírez-Ojeda G, Medina-García G, Rodríguez-Moreno VM, de la Mora-Orozco C, Florez-López H, Durán-Puga N. 2014. Índices de extremos térmicos en las Llanuras Costeras del Golfo Sur en México. *Revista Mexicana de Ciencias Agrícolas* 5 (10): 1843–1857.
- Zhang X, Alexander L, Hegerl GC, Jones P, Tank AK, Peterson TC, Trewin B, Zwiers FW. 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Climate Change* 2 (6): 851–870. <https://doi.org/10.1002/wcc.147>
- Zhang X, Feng Y, Chan R. 2018. Introduction to RClimDex v1.9. Climate Research Division. Toronto, Canada. <https://github.com/ECCC-CDAS/RClimDex/blob/master/inst/doc/manual.pdf> (Retrieved: May 2023).

Agrociencia

## VEGETATIVE COVER OF A MINE TAILINGS WITH BERMUDA GRASS (*Cynodon dactylon* L.) TO MITIGATE POLLUTION

Elizabeth Hernández-Acosta<sup>1\*</sup>, Emma Ángela Acevedo-Girón<sup>1</sup>,  
Edmundo Robledo-Santoyo<sup>1</sup>, Jorge Luis Castellón-Montelongo<sup>1</sup>

<sup>1</sup>Universidad Autónoma Chapingo. Departamento de Suelos. Carretera México-Texcoco km 38.5, Texcoco, State of Mexico, Mexico. C. P. 56230.

\* Author for correspondence: ehernandez@chapingo.mx

### ABSTRACT

The vegetative cover of mine tailings with grasses has environmental benefits and positive impacts on public health by improving air and water quality, as well as the overall well-being of surrounding communities. This study evaluated the ability of *Cynodon dactylon* L. grass in the cover of a mine tailing using three doses of vermicompost ( $V_{low}$  [60 Mg ha<sup>-1</sup>],  $V_{medium}$  [80 Mg ha<sup>-1</sup>], and  $V_{high}$  [100 Mg ha<sup>-1</sup>]) to improve the conditions of the site, which was physically and chemically characterized. The concentrations of lead (Pb), cadmium (Cd), nickel (Ni), and zinc (Zn) were determined before and during the experiment. Ninety-six and 202 days after planting (dap), grass was harvested to determine the concentrations of the potentially toxic elements (PTE) in the root and aerial sections. The production of dry matter and the growth of the grass were evaluated. Results showed that, before the experiment was established, the tailing had a low concentration of organic matter. After incorporating the vermicompost, an increase was observed in the concentrations of phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg). Ninety-six days after planting, in the treatment with the low dose of vermicompost, *C. dactylon* absorbed 202.13 mg Pb kg<sup>-1</sup>, 37.26 mg Ni kg<sup>-1</sup>, and 164.82 mg Zn kg<sup>-1</sup> in its roots. Also at 96 dap, the highest PTE concentrations were found in the treatments with the highest dose of vermicompost. The greatest production of dry matter (231.55 kg ha<sup>-1</sup> at 96 dap) and growth of the grass (9.7 cm, 73 dap) occurred in the treatment with the high dose of vermicompost, which highlights its efficiency in favoring its development and improving the conditions of the tailing. The absorption of the PTE by the grass highlights its contribution towards the reduction of dispersion and runoff of particles from tailings.

**Keywords:** mine residues, potentially toxic elements, organic amendments, vegetative cover.

### INTRODUCTION

Globally, mining is an activity that plays an important role in the economies of many countries. It not only produces jobs and profits, but it also contributes significantly to the gross domestic product, boosts innovation, and promotes investment in infrastructure and technological development. However, it faces substantial challenges regarding environmental impacts, such as soil, water, and air pollution, the management of mine

**Citation:** Hernández-Acosta E, Acevedo-Girón EÁ, Robledo-Santoyo E, Castellón-Montelongo JL. 2024. Vegetative cover of a mine tailings with Bermuda grass (*Cynodon dactylon* L.) to mitigate pollution. *Agrociencia* 58(5): 641-655. <https://doi.org/10.47163/agrociencia.v58i5.3140>

**Editor in Chief:**  
Dr. Fernando C. Gómez Merino

Received: January 02, 2024.  
Approved: May 14, 2024.

**Published in Agrociencia:**  
July 03, 2024.

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



tailings, erosion, and the loss of biodiversity (Singh *et al.*, 2020b). Likewise, it creates problems such as the displacement of communities, social conflicts, and repercussions in public health and activities such as agriculture (Islam *et al.*, 2020).

Mine tailings are residues composed of ground rocks and effluents resulting from mineral processing that accumulate in ecosystems after the extraction of economically valuable minerals, generating environmental problems in open areas (Xiaolong *et al.*, 2021). The presence of these residues in communities leads to a public health issue when strong winds or water spread surface particles from the tailings, which contain As, Hg, Pb, and Cd, among others. Inhaling these particles affects the health of people living in nearby areas, including gastrointestinal and respiratory disorders, irritation of the nose and eyes, and other issues that pose a concern to the general population (Mpanza *et al.*, 2020).

Vegetative cover is a technique used in the restoration and rehabilitation of areas affected by human activities, such as mining (Márquez-Huitzil *et al.*, 2022). It involves the establishment of plants on degraded or altered surfaces in order to restore elements of the ecosystem, such as soil, water, and biodiversity, as well as preventing erosion and pollution (Marcelo-Silva *et al.*, 2023). Bermuda grass (*Cynodon dactylon* L.) is used to restore mine tailings and eliminate or stabilize potentially toxic elements. Its resistance to adverse conditions such as drought or salinity (Zhang *et al.*, 2023), along with its rapid growth and ability to spread via stolons and rhizomes, make it a valuable plant. This species plays an important role in covering disrupted areas, thus promoting their recovery (Yang *et al.*, 2016). Under these conditions, it facilitates ecological succession and provides habitats for other plants and local fauna.

In mine tailings, colonization and succession with native plants is recommended, including those that facilitate the growth and development of young species and those with lower strata. These sites, known as vegetation islands, play an important part in mitigating the dispersion and runoff of particles (Duarte-Zaragoza *et al.*, 2020). Establishing plants in the tailings helps the ecosystem to continue accepting the mining activity. Even after the mine ceases to operate, the site will receive many benefits from the presence of the plants. In this task, the incorporation of organic materials such as vermicompost is beneficial since it improves the quality of the tailings by providing nutrients for the plants, improving water retention, and stimulating microbial activity, among other crucial factors for their growth and development. In this way, the success of the vegetative cover is strengthened (Ma *et al.*, 2022).

This study analyzed the growth, development, and ability of *C. dactylon* to absorb potentially toxic elements (PTE) in mine tailings conditioned with vermicompost. The goal is to propose this species as a viable alternative in the vegetative cover to mitigate pollution and health problems derived from the dispersion and runoff of particles in surrounding areas.

## MATERIALS AND METHODS

### Experimental site

The experiment was conducted at the Dos Carlos mine tailings in Pachuca, Hidalgo, Mexico (20° 06' N, 98° 43' W, and 20° 06' N, 98° 42' W), within the Pachuca-Real del Monte mining district, in the Pachuca Mountain Range, a metallogenic region in the Mexican Neovolcanic Axis, where primary extraction in colonial times focused on silver. The area of the tailings has an extension of 51.4 ha, a mean height of 20 m, and an estimated amount of 107 659 225 Mg. The area presents temperatures ranging between 10 and 16 °C, an average rainfall between 400 and 900 mm, and a temperate semidry climate (INEGI, 2022). Plantations were performed in July, and harvests took place on the first week of February; during this time, the plants in the mine tailing were exposed to both rain and drought.

### Location of the experimental plot

A site representative of the conditions of the tailings (slope, drainage, exposure to the elements, accessibility, stability, and presence of vegetation) was selected (20° 06' 21.62'' N and 98° 42' 46.72'' W, at an altitude of 2435 m). *Cynodon dactylon* L. was chosen as the proposed vegetative cover for the tailings for its potential in the recovery of polluted areas (Rabêlo *et al.*, 2021), speedy growth, high biomass, well-developed root system, and tolerance to conditions of biotic and abiotic stress (Zhang *et al.*, 2023). Vermicompost was added to the tailings during plant establishment, which displayed an apparent density of 0.66 g cm<sup>-3</sup>, moderately alkaline pH (8.20), a concentration of organic matter of 28.02 %, inorganic N (51.33 mg kg<sup>-1</sup>), P (326.9 mg kg<sup>-1</sup>), K (914.16 mg kg<sup>-1</sup>), Ca (33.8 mg kg<sup>-1</sup>), Mg (63.96 mg kg<sup>-1</sup>), Pb (0.54 mg kg<sup>-1</sup>), Cd (0.09 mg kg<sup>-1</sup>), Ni (0.5 mg kg<sup>-1</sup>), and Zn (48.96 mg kg<sup>-1</sup>), in accordance with NOM-021-SEMARNAT-2000 (DOF, 2002). In general, the vermicompost had a high concentration of organic matter and phosphorous and a low concentration of PTE.

### Experimental design and statistical analysis

The experimental plot was established in the tailing using the completely randomized block experimental design, leading to a more homogenous plot and improving the accuracy of the comparison between treatments. The study incorporates three levels of vermicompost: a low dose, equivalent to 60 Mg ha<sup>-1</sup> (Vb); a medium dose, equivalent to 80 Mg ha<sup>-1</sup> (Vm); and a high dose, equivalent to 100 Mg ha<sup>-1</sup> (Va). Every dose was considered a treatment, with three repetitions. The plot measured 9 x 9 m and was divided into three blocks; three treatments were established in each block. Thus, a total of nine experimental units were obtained, each measuring 3 x 3 m. A distance of 50 cm was placed between blocks, and each block presented 11 rows in straight lines at a distance of approximately 27 cm.

The data from the variables evaluated on mine tailings and plant material samples were analyzed using a linear model,  $Y_{ijk} = \mu + T_i + B_j + \varepsilon_{ijk}$ , where  $Y_{ijk}$  = observations,

$\mu$  = general mean,  $T_i$  = effect of the  $i$ -th treatment,  $B_j$  = effect of the  $j$ -th block, and  $\varepsilon_{ijk}$  = experimental error. The statistical program SAS version 9 was used to perform the analysis of variance (ANOVA) and Tukey's test ( $p \leq 0.05$ ).

#### **Establishment and follow-up of the experiment**

The surface of the experimental plot was hardened by compacting, making it necessary to break the surface of the tailings. The three doses of vermicompost were then added to each corresponding treatment and mixed homogeneously to a depth of 10 cm. Next, in the autumn-winter cycle, 15 kg ha<sup>-1</sup> of *C. dactylon* were planted (0.0135 kg of seed per experimental unit); the seeds were planted at a depth of 1 to 2 cm on the rows, at a distance of 27 cm between rows. The seeds were then irrigated with a watering can twice a week for one month and a half; after this time, plants were irrigated depending on their requirements. Starting at germination, the average growth of the grass was recorded weekly in each experimental unit.

#### **Physical and chemical analysis of the tailing in the experimental plot**

The mine tailings were sampled at 0, 96, and 202 days after planting (dap), and a compound mixture was obtained from subsamples taken from each of the experimental units using the zigzag method, covering the entire experimental plot. The subsamples were taken at a depth of 5 to 10 cm according to NOM-021-SEMARNAT-2000 (DOF, 2002). Compound samples were analyzed in the laboratories of the Chapingo Autonomous University [Environmental Biotechnology Laboratory of the Department of Soils (LBA-Suelos-UACH) and the National Agrifood and Forestry Research and Services Laboratory (LANISAF)], following the procedures described in NOM-021-SEMARNAT-2000 (DOF, 2002), to determine apparent density, pH, percentage of organic matter, and concentration of inorganic N, P, K, Ca, Mg, Pb, Cd, Ni, and Zn.

#### **Sampling, harvest, and plant analysis**

After 96 and 202 dap, the grass was cut from the base of the stem (soil level) using pruning shears. At least 500 g of fresh grass and roots (9 root samples and 9 leaf samples per experimental unit) were taken for labeling. The plant material was washed, dried (in a stove at 75 °C until constant weight), and ground in an agate mortar. The concentration of Pb, Cd, Ni, and Zn present in each sample was determined following the AS-14 method described in NOM-021-SEMARNAT-2000 (DOF, 2002). The production of grass was evaluated, and the percentage of dry matter was obtained. For this purpose, the samples were placed in a forced-air oven at 50 °C for 48 h. At the end of this period, they were weighed at 18, 23, 27, 32, 49, and 73 dap using measuring tape. The measurements were taken on these dates because the plants began to display growth.

## RESULTS AND DISCUSSION

### Physical and chemical characteristics of the tailing

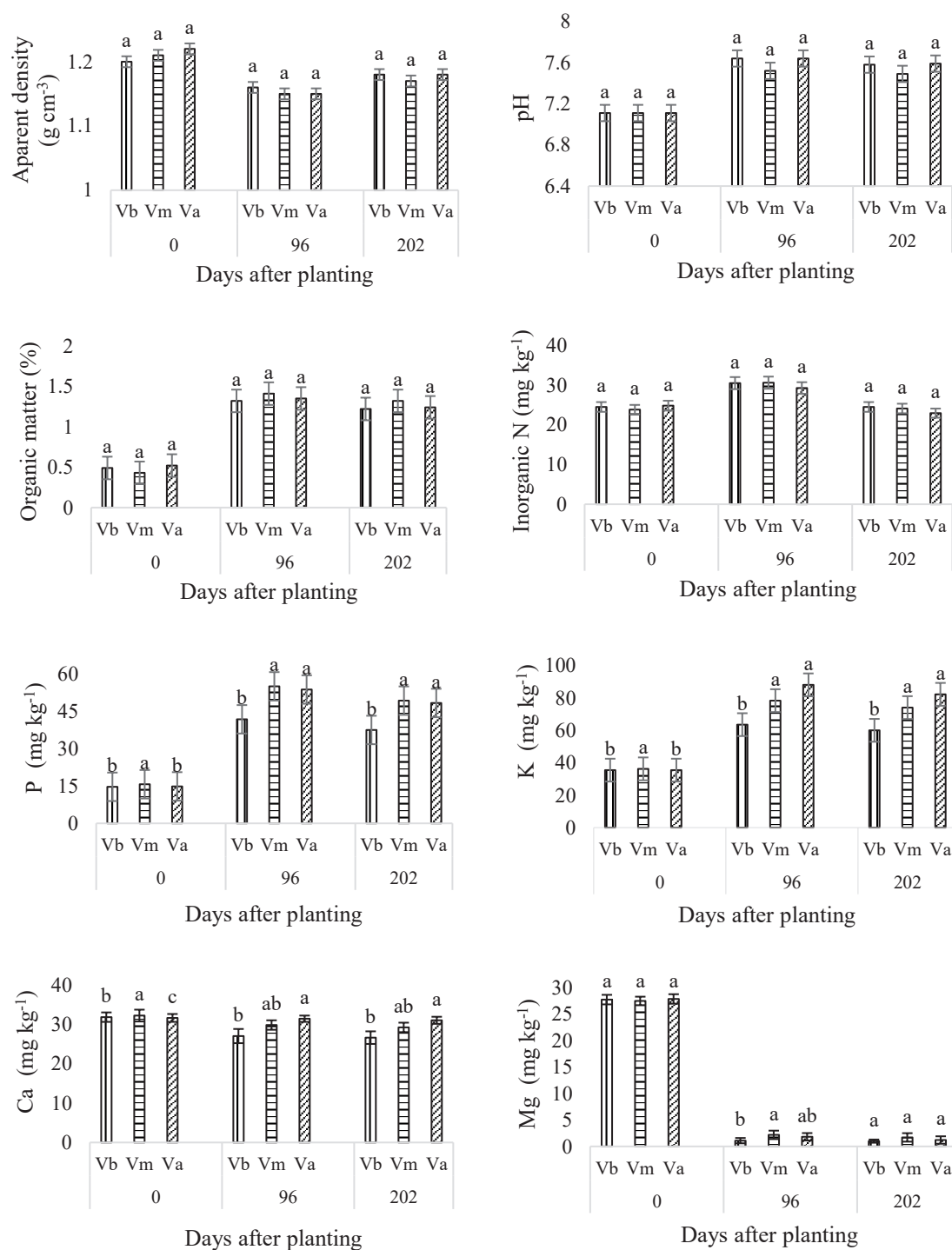
The mine tailings displayed an apparent density of  $1.21 \text{ g cm}^{-3}$ , a neutral pH of 7.11, a very low concentration of organic matter (0.48 %), a medium content of inorganic N ( $24.38 \text{ mg kg}^{-1}$ ), a high concentration of P ( $15.06 \text{ mg kg}^{-1}$ ) and K ( $35.49 \text{ mg kg}^{-1}$ ), a very low availability of Ca ( $31.8 \text{ mg kg}^{-1}$ ), and a medium availability of Mg ( $27.58 \text{ mg kg}^{-1}$ ). According to national and international standards for soils, the permissible limits of Pb ( $10.63 \text{ mg kg}^{-1}$ ), Cd ( $0.58 \text{ mg kg}^{-1}$ ), Ni ( $0.2 \text{ mg kg}^{-1}$ ), and Zn ( $36.21 \text{ mg kg}^{-1}$ ) were not exceeded (Council of the European Union, 1986; USEPA, 1996; Kabata-Pendias and Pendias, 2010).

According to the statistical analysis, with the establishment of *C. dactylon* at 0, 96, and 202 dap, the treatment that displayed the best results was the one with a concentration of 80 Mg of vermicompost per hectare. The variables that displayed differences between treatments were the concentrations of P, K, Ca, and Mg. An increase was observed in the concentrations of P and K with time, with the treatment performed at 96 dap displaying the highest values. For Mg, the concentrations decreased (Figure 1). Tukey's test displayed differences between treatments for the concentrations of P and K. In both cases, the highest means were presented with medium and high doses of vermicompost at 96 and 202 dap. Both contents were considered high, according to determinations by NOM-021-SEMARNAT-2000 (DOF, 2002). The concentrations of P and K increased over time; the addition of vermicompost resulted in high concentrations at the end of the experiment in the plot. The mine tailings without the incorporation of vermicompost presented values of  $15.06 \text{ mg kg}^{-1}$  (P) and  $35.49 \text{ mg kg}^{-1}$  (K); at 96 dap, the values were  $55 \text{ mg kg}^{-1}$  (P) and  $914.16 \text{ mg kg}^{-1}$  (K) (Figure 1). A study by Paradelo (2013) concluded that the incorporation of organic materials such as compost and vermicompost into mine tailings increase the accumulation of P and K in plants, since they provide nutrients (Lukashe *et al.*, 2019; Singh *et al.*, 2020a).

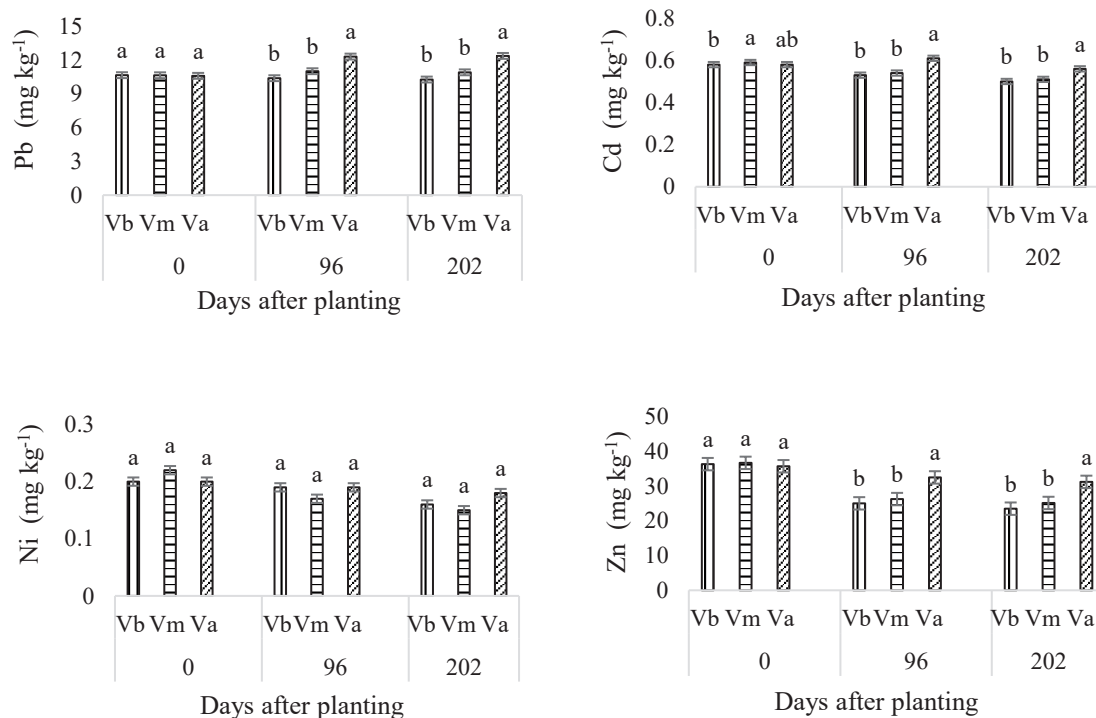
Despite the lack of differences between treatments for apparent density, pH, organic matter, and concentration of N, these variables increased in value with time (Figure 1). At 202 dap, the percentage of organic matter in the experimental plot increased from 0.48 to 1.32 % as a result of the incorporation of vermicompost. Bautista-Gabriel *et al.* (2016) obtained similar data as a result of a greenhouse experiment in which they planted *Lolium perenne* grass in mine tailings and added compost; these researchers increased the percentage of organic matter from 0 to 1.5 %.

### Lead, cadmium, nickel, and zinc concentration in the tailing

The statistical analyses displayed differences between treatments for the concentrations of Pb, Cd, and Zn. In general, the highest concentration of PTE was found in the treatments with the highest doses of vermicompost, at 96 and 202 dap. Zn was found in the highest concentration, followed by Pb and Cd; however, none of the three surpassed the permissible limits according to international standards for soils (Figure 2).



**Figure 1.** Physical and chemical characteristics of the mine tailing with the establishment of the *Cynodon dactylon* grass at 0, 96, and 202 days after planting. Means ± EE in subfigures with different letters show statistically significant differences (Tukey,  $p \leq 0.05$ ). V<sub>b</sub>: 60 Mg vermicompost ha<sup>-1</sup>; V<sub>m</sub>: 80 Mg vermicompost ha<sup>-1</sup>; V<sub>a</sub>: 100 Mg vermicompost ha<sup>-1</sup>.



**Figure 2.** Concentrations of lead, cadmium, nickel, and zinc at the mine tailing, with the establishment of *Cynodon dactylon* grass and vermicompost at 0, 96, and 202 days after planting. Means  $\pm$  EE in subfigures with different letters show statistically significant differences (Tukey,  $p \leq 0.05$ ).  $V_b$ : 60 Mg vermicompost  $ha^{-1}$ ;  $V_m$ : 80 Mg vermicompost  $ha^{-1}$ ;  $V_a$ : 100 Mg vermicompost  $ha^{-1}$ .

The highest concentration of Pb was recorded at 202 dap ( $12.37 \text{ mg kg}^{-1}$ ) in the treatment with the highest dose of vermicompost. This element was observed to increase in the tailings with time, although the permissible limits were not surpassed (Figure 2). Higher Pb concentrations ( $34 \text{ mg kg}^{-1}$ ) were reported by Hernández-Acosta *et al.* (2009) when evaluating concentrations of PTE in the same mine tailings. Regrading increases in Pb, the use of vermicompost is reported to cause its adsorption, particularly on the surface of the soil. Its least acidic pH values increase its adsorption (Barriga-Vélez *et al.*, 2023) due to the formation of less soluble chemical species and the precipitation of Pb in the form of Pb-phosphate (McBride *et al.*, 2019).

With a high dose of vermicompost, the concentration of Cd increased at 96 dap ( $0.61 \text{ mg kg}^{-1}$ ) and decreased at 202 dap ( $0.56 \text{ mg kg}^{-1}$ ); these concentrations surpass the normal limit of  $0.35 \text{ mg kg}^{-1}$  in the soil, which is tolerable for plants according to NOM-021-SEMARNAT-2000 (DOF, 2002). However, these concentrations are not considered dangerous since they are below  $1 \text{ mg kg}^{-1}$  (Figure 2). Regarding the limit established for the European Union, this element remained below the limit (Kabata-Pendias and

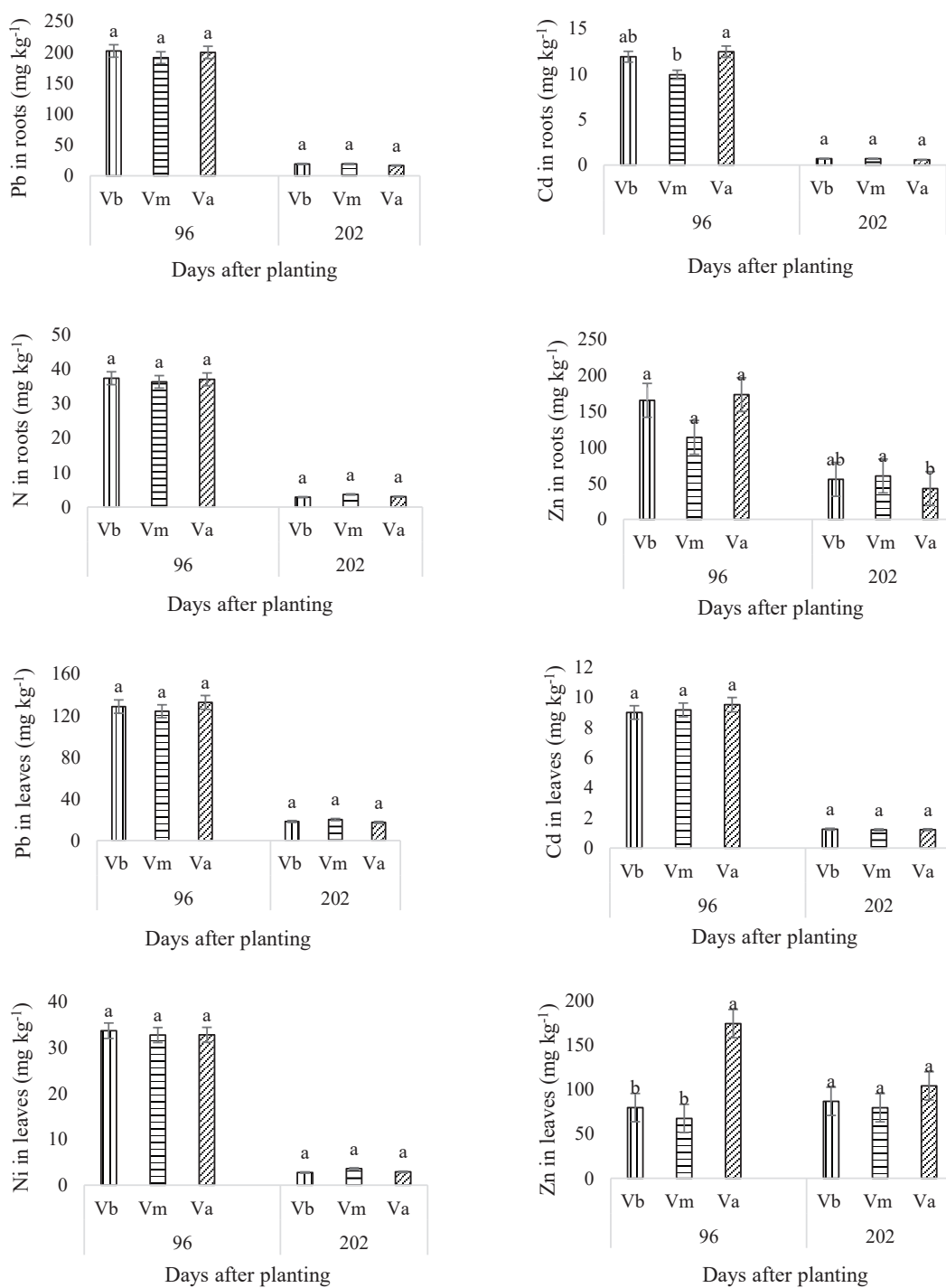
Pendias, 2010). The increase displayed with Cd could have occurred with the addition of vermicompost, but also due to this element having a higher mobility than most PTEs due to the relative solubility of its salts and hydroxides (Kabata-Pendias and Pendias, 2010). On the other hand, its decrease at 202 dap is attributed to its adsorption by the grass, since it is a metal with a greater tendency to accumulate in plants (Reyes *et al.*, 2016), such as *Lolium multiflorum* grass, which is tolerant to Cd and has the potential for hyperaccumulation due to its wide distribution, capability of absorption, tolerance, and accumulation of PTE in its plant tissues (Wang *et al.*, 2020).

The behavior of the Zn concentration was different. It decreased from 36.66 (at 0 dap in treatment  $V_m$ ) to 31.19 mg kg<sup>-1</sup> (at 202 dap in treatment  $V_a$ ) and did not surpass the permitted limit according to the standards of the United States Environmental Protection Agency and the European Community (Council of the European Union, 1986; USEPA, 1996). The reduction of Zn concentration is related to its ability to form complexes with the vermicompost added to the tailings, which originate from the transformation of the nutrient from the solid phase to forms available to plants; in this condition, the absorption of the metal is favored. Similar findings were reported by Bautista-Gabriel *et al.* (2016), who assessed the effect of compost on mine tailings in a greenhouse by planting *Lolium perenne* and discovered a decrease in the Zn concentration in the tailings at 30 and 60 dap. Zhang *et al.* (2023) showed that *Cynodon dactylon* is a genetically adequate grass to reproduce in mine tailings with high concentrations of Zn. They suggest that it can be used as a cover plant in areas contaminated with this element. Its shoots, stolons, and rhizomes allow it to fulfill various applications and physiological functions (Chen *et al.*, 2021).

#### **Lead, cadmium, nickel, and zinc concentration in *Cynodon dactylon***

In general terms, the roots concentrated a higher amount of EPT than in the aerial section (Figure 3). In the roots, differences were identified between treatments regarding the concentrations of Cd and Zn. The highest concentrations of the four EPTs were registered at 96 dap, with a pronounced reduction at 202 dap. This can be attributed to factors such as the differential absorption of the metals by the roots and the processes of metabolization and translocation inside the plant (Xu *et al.*, 2021).

In the roots, out of the four metals, Pb presented a notable decrease, dropping from 202.13 mg kg<sup>-1</sup> at 96 dap with the lowest dose of vermicompost ( $V_b$ ) to 16.65 mg kg<sup>-1</sup> at 202 dap with the highest dose of vermicompost ( $V_a$ ). Similarly, Zn concentrations decreased from 172.79 (at 96 dap in the  $V_a$  treatment) to 42.64 mg kg<sup>-1</sup> (at 202 dap in the  $V_a$  treatment) (Figure 3). According to Kabata-Pendias and Pendias (2010), these values fall within the phytotoxicity range. Particularly, Pb can induce toxicity problems in plants, manifesting through changes in coloration. Nevertheless, no signs of this occurrence were observed in *C. dactylon* in this experiment. Mahohi and Raiesi (2021) report that this grass is suitable for phyto-remediating sites contaminated with potentially toxic trace oligo-elements. It is important to highlight that grasses in general have shown remarkable tolerance to the presence of PTE in mine tailings (Amezcu-Ávila *et al.*, 2020).



**Figure 3.** Concentrations of lead, cadmium, nickel, and zinc in roots and aerial section of *Cynodon dactylon* grass planted in the mine tailing conditioned with vermicompost. Means  $\pm$  EE in subfigures with different letters show statistically significant differences (Tukey,  $p < 0.05$ ). V<sub>b</sub>: 60 Mg vermicompost ha<sup>-1</sup>; V<sub>m</sub>: 80 Mg vermicompost ha<sup>-1</sup>; V<sub>a</sub>: 100 Mg vermicompost ha<sup>-1</sup>.

In the aerial section of *C. dactylon*, there were differences at 96 and 202 dap for the concentration of Zn (Figure 3). The highest concentrations in the aerial section at 96 (174.18 mg kg<sup>-1</sup>) and 202 dap (104.07 mg kg<sup>-1</sup>) were shown in the treatments with the highest dose of vermicompost (V<sub>a</sub>), resulting in a notable reduction of the Zn contents in the tailings. This confirms the ability of *Cynodon dactylon* to accumulate Zn in its roots and to translocate this element, storing phytotoxic amounts of it (Kabata-Pendias and Pendias, 2010). In a similar study, Bautista-Gabriel *et al.* (2016) found a significant reduction in the contents of PTE, including Zn, when applying vermicompost in mine tailings where *Lolium perenne* grass grew. The use of vermicompost is common in agricultural soils for the growth of *Cynodon dactylon* (Erdawati *et al.*, 2023); furthermore, the application of organic amendments in contaminated sites is attributed with the ability to reduce the bioavailability of PTE (Perea-Vélez *et al.*, 2015).

#### Production and growth of *C. dactylon* at 96 and 202 dap

At 96 dap, no differences were observed in the variable of dry matter between treatments. The treatment with the highest dose of vermicompost (V<sub>a</sub>) displayed the greatest production of dry matter (Table 1). At 202 dap, differences were found between treatments. The greatest yield was observed in treatment V<sub>m</sub>; the production of dry matter at 96 dap was greater than that obtained at 202 dap. This reduction in the production of grasses is directly related to the period of lethargy; in the winter, temperatures in the mine tailing reached 0 °C, along with some frosts, causing the mature plants to become dormant (Feuchter, 2018). This phenomenon can be seen on the field, when the aerial section of the grasses turns brown.

**Table 1.** Production of dry matter (kg ha<sup>-1</sup>) of *Cynodon dactylon* grass at 96 and 202 days after planting at the Dos Carlos mine tailing in Pachuca, Hidalgo, Mexico.

Days after planting	Treatments		
	V <sub>b</sub>	V <sub>m</sub>	V <sub>a</sub>
96	79.37 a	152.45 a	231.55 a
202	50.08 b	127.54 a	107.95 ab

Means in the same row with different letters are statistically different (Tukey,  $p \leq 0.05$ ). V<sub>b</sub>: 60 Mg vermicompost ha<sup>-1</sup>; V<sub>m</sub>: 80 Mg vermicompost ha<sup>-1</sup>; V<sub>a</sub>: 100 Mg vermicompost ha<sup>-1</sup>.

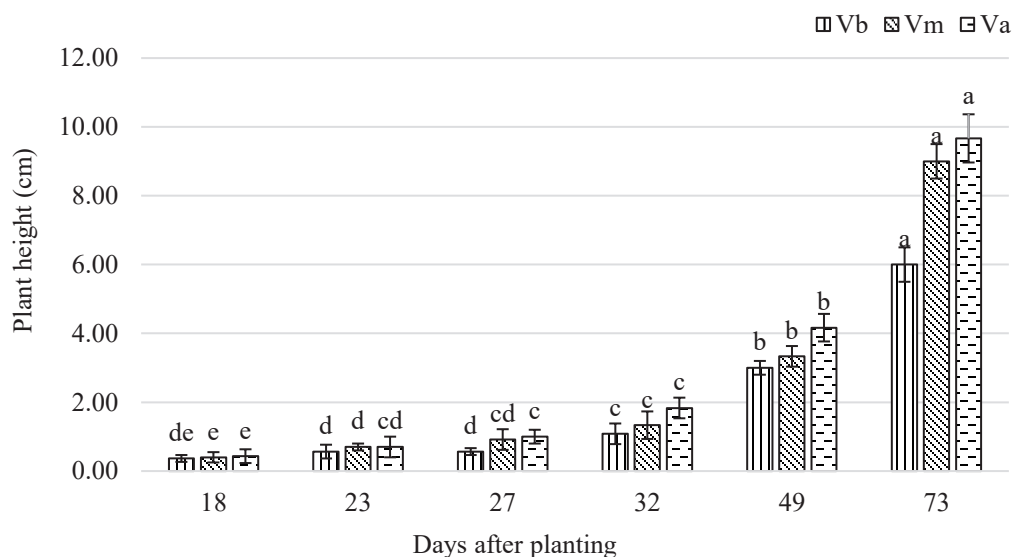
It is normal for the production of dry matter in *C. dactylon* to vary with time, particularly in temperate climates with well-defined seasons (Ibrahim *et al.*, 2023). Another factor of influence is irrigation, since water deficit may have a negative impact on the production of dry matter, according to Calderón-Vera and Rivera-Fernandez (2018).

In semi-arid regions without irrigation, *C. dactylon* produces between 8 and 12 Mg ha<sup>-1</sup> of dry matter per year (Cavalcante, 2013). With an irrigation system, Calderón-Vera and Rivera-Fernandez (2018), in a farm in the province of Manabí, Ecuador, found that the production of biomass in this species ranged between 0.22 and 0.94 kg m<sup>-2</sup> under different irrigation levels. In turn, Feuchter (2018) mentions that in a prairie with an irrigation system, the optimum establishment of *C. dactylon* is reached 6 months after planting, achieving yields of up to 40 Mg ha<sup>-1</sup> of dry matter per year. Although this investigation did not evaluate the annual production of dry matter due to the two samplings performed (one in autumn and another in winter), it was observed that the productivity was limited by the adverse conditions of the mine tailing and the lack of irrigation since the crop was rainfed. As a consequence, the highest production reached was 231 kg ha<sup>-1</sup> of dry matter at 96 dap (in autumn), when the vermicompost had time to mineralize, there was a certain moisture in the mine tailing, and the temperature was not very unfavorable.

The results of the analysis of variance for the average data in the variable of height in time (days) suggest that there are significant differences between treatments. The germination of *C. dactylon* in the mine tailing was produced at 18 dap, a period within the range of 3 to 21 d, according to Delgado-Caballero *et al.* (2017), who studied the germination of *C. dactylon* in mine residues. They highlight that the germination of this species is affected by the presence of PTE and pH. These authors obtained a percentage of germination that ranged between 28 and 35 %, which dropped to 18 % at pH values lower than 7.

The growth of *C. dactylon* started becoming noticeable at 32 dap. In general, the incorporation of vermicompost had a positive effect on the growth of the grass (Figure 4). At 73 dap, with the high dose of vermicompost ( $V_a$ ), the grass presented a difference in height of 4 cm in comparison to the treatment with a lowest dose ( $V_b$ ), and a difference of 1 cm in height against  $V_m$ . The greatest development in *C. dactylon* was shown when using the highest dose (100 Mg ha<sup>-1</sup>). This confirms, along with the dry matter production results (Table 1), that grasses were more productive in treatment  $V_a$ . The success of the growth of *C. dactylon* in the mine tailing was due to the vermicompost. This fertilizer acted as a source of nutrients, including organic nitrogen, which is gradually released and made available to plants once mineralized. This is supported by Ilahi *et al.* (2020), who explain how organic fertilizers, such as vermicompost, release this element and make it available to plants. The highest grass growth in this study was obtained with a high dose of vermicompost, which increased the availability of nutrients such as nitrogen (Santos *et al.*, 2022).

In a study by García-Amador and Castillo-Delgado (2015), *C. dactylon* was planted in contaminated soil from islets in Cuernavaca-Xochimilco, Mexico, which had 7.7 % organic matter at the beginning. The grass crop was irrigated by hand with distilled water, and 10 cm of growth was observed 10 weeks after planting (70 d), which is consistent with the results of this study at 73 dap. It is important to note that in this study, irrigation was carried out once a week until 30 dap, and the fertility of the mine tailing was significantly lower than that of the soil.



**Figure 4.** Average growth of *Cynodon dactylon* grass planted at the Dos Carlos mine tailing in Pachuca, Hidalgo, Mexico, under the effect of three vermicompost treatments. Means  $\pm$  EE in subfigures with different letters show statistically significant differences (Tukey,  $p \leq 0.05$ ).  $V_b$ : 60 Mg vermicompost  $ha^{-1}$ ;  $V_m$ : 80 Mg vermicompost  $ha^{-1}$ ;  $V_a$ : 100 Mg vermicompost  $ha^{-1}$ .

## CONCLUSIONS

*Cynodon dactylon* grass in mine tailing demonstrated its ability to grow and develop when 100 Mg  $ha^{-1}$  of vermicompost was applied. The highest production of dry matter facilitated the concentration of PTE in plant tissues, both in the root and aerial. This ability confirms the use of grass in vegetative cover projects in mine tailings, with the goal of reducing particle dispersion and runoff, as well as mitigating contamination and respiratory diseases in populations near the mine tailings. This study helps to establish an effective and sustainable strategy to mitigate some of the environmental impacts caused by mine tailings.

## ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Chapingo Autonomous University, through the General Directorate of Research and Graduate Studies and the Department of Teaching, Research and Soil Services, for financing this research.

## REFERENCES

Amezcuca-Ávila AV, Hernández-Acosta E, Díaz-Vargas P. 2020. Fitorremediación de residuos de minas contaminados con metales pesados. *Revista Iberoamericana de Ciencias* 7 (1): 79–91.

- Barriga-Vélez MA, Ramírez-Vargas LC, López-Barrera EA, Peña-Rincón CA. 2023. Potential ecological risk index for metals in a grazing area, Guasca, Cundinamarca. *Revista Facultad de Ingeniería Universidad de Antioquia* 106: 103–112. <https://doi.org/10.17533/udea.redin.20210422>
- Bautista-Gabriel EJ, Hernández-Acosta E, Cristóbal-Acevedo D, Quintero-Lizaola R, Díaz-Vargas P, Robledo-Santoyo E. 2016. Extracción de metales pesados por *Lolium perenne* en residuos de mina. *Revista Iberoamericana de Ciencias* 3 (5): 1–16.
- Calderón-Vera MA, Rivera-Fernandez RD. 2018. Effect of the deficit irrigation through sprinkler irrigation on the yield of grass *Cynodon dactylon*. *Revista Espamciencia* 9 (2): 91–95.
- Cavalcante ACR. 2013. Producción y utilización de forrajeras convencionales cultivadas en el Semiárido Brasileño. In Iñiguez RL. (ed.), *La Producción de Rumiantes Menores en las Zonas Áridas de Latinoamérica*. International Center for Agricultural Research in the Dry Areas: Brasilia, Brazil, pp: 313–339.
- Chen S, Xu X, Ma Z, Liu J, Zhan B. 2021. Organ-specific transcriptome analysis identifies candidate gene involved in the stem specialization of bermudagrass (*Cynodon dactylon* L.). *Frontiers in Genetics* 23 (12): 678673. <https://doi.org/10.3389/fgene.2021.678673>
- Council of the European Union. 1986. Directiva del Consejo de 12 junio 1986 relativa a la protección del medio ambiente y, en particular, de los suelos, en la utilización de lodos de depuradora en agricultura. *Diario Oficial de las Comunidades Europeas* L181: 6–12.
- Delgado-Caballero MR, Alarcón-Herrera MT, Valles-Aragón MC, Melgoza-Castillo A, Ojeda-Barrios DL, Leyva-Chávez A. 2017. Germination of *Bouteloua dactyloides* and *Cynodon dactylon* in a multi-polluted Soil. *Sustainability* 9 (1): 81. <https://doi.org/10.3390/su9010081>
- DOF (Diario Oficial de la Federación). 2002. NORMA Oficial Mexicana NOM-021-SEMARNAT-2000, que establece las especificaciones de fertilidad, salinidad y clasificación de suelos, estudio, muestreo y análisis. Gobierno de México. Secretaría de Medio Ambiente y Recursos Naturales. Ciudad de México, México. <https://elsemarnat.info/normas/nom-021/> (Retrieved: February 2024).
- Santos, P. L. F. D., Nascimento, M. V. L. D., Godoy, L. J. G. D., Zabotto, A. R., Tavares, A. R., & Bôas, R. L. V. (2022). Influence of irrigation frequency and nitrogen concentration on Tifway 419 bermudagrass in Brazil. *Revista Ceres*, 69(5), 578-585. <https://doi.org/10.1590/0034-737X202269050011>
- Duarte-Zaragoza VM, Pérez-Hernández VS, Hernández-Acosta E, Villanueva-Morales A. 2020. Estudio exploratorio de la acumulación de plomo y cobre en *Prosopis laevigata* en depósitos mineros. *Ecosistemas y Recursos Agropecuarios* 7 (2).
- Erdawati E, Suryani E, Nanda EV. 2023. Application biochar-vermicompost mixture as a media used for *Cynodon dactylon* L. growth. *AIP Conference Proceedings* 2720 (1): 040011. <https://doi.org/10.1063/5.0156814>
- Feuchter FR. (2018). Siembra de zacate bermuda *Cynodon dactylon* (L.) Pers. (grama gigante) con semilla de grano escarificado para praderas forrajeras de riego en Sonora. Centro Regional Universitario del Noroeste: Ciudad Obregón, México. 12 p.
- García-Amador EM, Castillo-Delgado BG. 2015. Depuración de suelos contaminados con metales pesados, una implicación para la transición agroecológica. In Cruz G, López AB. (eds.), *Re-descubriendo el suelo: su importancia ecológica y agrícola*. Universidad Nacional Autónoma de México: Ciudad de México, México, pp: 187–201.
- Hernández-Acosta E, Mondragón-Romero E, Cristóbal-Acevedo D, Rubiños-Panta JE, Robledo-Santoyo E. 2009. Vegetación, residuos de mina y elementos potencialmente tóxicos de un jal

- de Pachuca, Hidalgo, México. *Revista Chapingo Serie Ciencias Forestales y del Ambiente* 15 (2): 109–114.
- Ibrahim S, Nuratu A, Muktar A. 2023. Comparative yield and nutrient contents between rainfed and irrigated Bermuda Grass (*Cynodon dactylon*) in Bauchi State, Nigeria. *Journal of Pure and Applied Agriculture* 7 (3): 8–14.
- Ilahi H, Hidayat K, Adnan M, Rehman FU, Tahir R, Saeed MS, Shah SWA, Toor MD. 2020. Accentuating the impact of inorganic and organic fertilizers on agriculture crop production: A review. *International Journal of Pure and Applied Bioscience* 9 (1): 36–45. <https://doi.org/10.18782/2582-2845.8546>
- INEGI (Instituto Nacional de Estadística y Geografía). 2022. Aspectos geográficos Hidalgo 2021. Aguascalientes, México. 48 p. <https://www.inegi.org.mx> (Retrieved: January 2024).
- Islam K, Vilaysouk X, Murakami S. 2020. Integrating remote sensing and life cycle assessment to quantify the environmental impacts of copper-silver-gold mining: A case study from Laos. *Resources, Conservation and Recycling* 154: 1–13 <https://doi.org/10.1016/j.resconrec.2019.104630>
- Kabata-Pendias A, Pendias H. 2010. Trace elements in soils and plants (Fourth edition). CRC Press: Boca Raton, FL, USA. 548 p. <https://doi.org/10.1201/b10158>
- Lukashe NS, Mupambwa HA, Mnkeni PNS. 2019. Changes in nutrients and bioavailability of potentially toxic metals in mine waste contaminated soils amended with fly ash enriched vermicompost. *Water, Air, and Soil Pollution* 230 (12): 1–17. <https://doi.org/10.1007/s11270-019-4343-2>
- Ma H, Zhao S, Hou J, Feyissa T, Duan Z, Pan Z, Zhang K, Zhang W. 2022. Vermicompost improves physicochemical properties of growing medium and promotes plant growth: A meta-analysis. *Journal of Soil Science and Plant Nutrition* 22 (3): 3745–3755. <https://doi.org/10.1007/s42729-022-00924-7>
- Mahohi A, Raiesi F. 2021. The performance of mycorrhizae, rhizobacteria, and earthworms to improve Bermuda grass (*Cynodon dactylon*) growth and Pb uptake in a Pb-contaminated soil. *Environmental Science and Pollution Research* 28 (3): 3019–3034. <https://doi.org/10.1007/s11356-020-10636-z>
- Marcelo-Silva J, Ramabu M, Siebert SJ. 2023. Phytoremediation and nurse potential of Aloe plants on mine tailings. *International Journal of Environmental Research and Public Health* 20 (2): 1521. <https://doi.org/10.3390/ijerph20021521>
- Márquez-Huitzil R, Martínez-Garza C, Osorio-Beristain M. 2022. Adoptar los objetivos de la restauración ecológica como meta crucial al mitigar desechos mineros: una propuesta metodológica. *Acta Botánica Mexicana* 129: 1–37. <https://doi.org/10.21829/abm129.2022.2019>
- McBride MB, Kelch SE, Schmidt MP, Sherpa S, Martínez CE, Aristilde L. 2019. Oxalate-enhanced solubility of lead (Pb) in the presence of phosphate: pH control on mineral precipitation. *Environmental Science: Processes & Impacts* 21 (4): 738–747. <https://doi.org/10.1039/C8EM00553B>
- Mpanza M, Adam E, Moolla R. 2020. Dust deposition impacts at a liquidated gold mine village: Gauteng province in South Africa. *International Journal of Environmental Research and Public Health* 17 (14): 4929. <https://doi.org/10.3390/ijerph17144929>
- Paradelo R. 2013. Utilización de materiales compostados en la rehabilitación potencial de espacios afectados por residuos mineros y suelos de mina. *Boletín Geológico y Minero* 124 (3): 405–419.

- Perea-Vélez YS, Carrillo-González R, Solís-Domínguez FA, González-Chávez MCA. 2015. Fitorremediación de un residuo de mina asistida con enmiendas y bacterias promotoras de crecimiento. *Revista Latinoamericana de Biotecnología Ambiental y Algal* 6 (1): 31–49. <https://doi.org/10.7603/s40682-015-0003-4>
- Rabêlo FHS, Vangronsveld J, Baker AJ, van der Eent A, Alleoni LRF. 2021. Are grasses really useful for the phytoremediation of potentially toxic trace elements? A review. *Frontiers in Plant Science* 12: 778275. <https://doi.org/10.3389/fpls.2021.778275>
- Reyes YC, Vergara I, Torres OE, Díaz-Lagos M, González EE. 2016. Contaminación por metales pesados: Implicaciones en salud, ambiente y seguridad alimentaria. *Revista Ingeniería Investigación y Desarrollo* 16 (2): 66–77. <http://dx.doi.org/10.19053/1900771x.v16.n2.2016.5447>
- Singh A, Karmegam N, Singh GS, Bhadauria T, Chang SW, Awasthi MK, Sudhakar S, Arunachalam KD, Biruntha M, Ravindran B. 2020a. Earthworms and vermicompost: an eco-friendly approach for repaying nature's debt. *Environmental Geochemistry and Health* 42: 1617–1642. <https://doi.org/10.1007/s10653-019-00510-4>
- Singh S, Sukla LB, Goyal SK. 2020b. Mine waste and circular economy. *Materials Today: Proceedings* 30 (2): 332–339. <https://doi.org/10.1016/j.matpr.2020.01.616>
- USEPA (United States Environmental Protection Agency). 1996. Soil screening guidance: technical background document. EPA/540/R-95/128. Office of Solid Waste and Emergency Response: Washington, DC, USA. [https://archive.epa.gov/region9/superfund/web/pdf/ssg\\_nonrad\\_technical-2.pdf](https://archive.epa.gov/region9/superfund/web/pdf/ssg_nonrad_technical-2.pdf) (Retrieved: January 2024).
- Wang J, Zhao J, Feng S, Zhang J, Gong S, Qiao K, Zhou A. 2020. Comparison of cadmium uptake and transcriptional responses in roots reveal key transcripts from high and low-cadmium tolerance ryegrass cultivars. *Ecotoxicology and Environmental Safety* 203: 110961. <https://doi.org/10.1016/j.ecoenv.2020.110961>
- Xiaolong Z, Shiyu Z, Hui L, Yingliang Z. 2021. Disposal of mine tailings via geopolymerization. *Journal of Cleaner Production* 284: 124756. <https://doi.org/10.1016/j.jclepro.2020.124756>
- Xu S, Zhao Q, Qin C, Qin M, Lee J, Li C, Li Y, Yang, J. 2021. Effects of vegetation restoration on accumulation and translocation of heavy metals in post-mining areas. *Land Degradation and Development* 32 (5): 2000–2012. <https://doi.org/10.1002/ldr.3861>
- Yang SX, Liao B, Yang ZH, Chai LY, Li JT. 2016. Revegetation of extremely acid mine soils based on aided phytostabilization: A case study from southern China. *Science of the Total Environment* 562: 427–434. <https://doi.org/10.1016/j.scitotenv.2016.03.208>
- Zhang B, Sun Q, Chen Z, Shu F, Chen J. 2023. Evaluation of zinc tolerance and accumulation in eight cultivars of bermudagrass (*Cynodon* spp.): Implications for zinc phytoremediation. *BioMetals* 36: 1377–1390. <https://doi.org/10.1007/s10534-023-00524-7>

