Responses to irrigation and defoliation of dry tropical woody forage species †

[Respuestas al riego y la defoliación de especies leñosas forrajeras del trópico seco]

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SUMMARY

Background. Tropical dry forests are abundant in trees with forage potential. However, there are few studies on their agronomic features aimed at their utilisation in intensive silvopastoral systems. **Objective**. To evaluate the establishment and growth in height, diameter, canopy cover, and biomass production of three forage tree species (*Leucaena leucocephala, Gliricidia sepium*, and *Moringa oleifera*) under the effects of two irrigation levels (irrigated and rainfed) and three defoliation levels (25, 50, and 75%), in order to obtain information for their agronomic management in the dry tropics. **Methodology.** A factorial experimental design in randomized blocks was used. Results were analyzed using general linear models. **Results.** During establishment, *L. leucocephala* reached a greater height and diameter than *M. oleifera* and *G. sepium*. After a 30-month monitoring period under irrigation and defoliation treatments, *L. leucocephala* was found to be the species with the greatest growth, but only *G. sepium* showed significant differences between irrigation treatments for height and diameter. In biomass production, *L. leucocephala* had the highest yield at 75% defoliation, with 103.03 ± 16.52 kg DM/ha, followed by *G. sepium*, also at 75% defoliation, with 79.62 ± 19.77 kg DM/ha. It was also observed that the species were not affected after three successive prunings with recovery periods of three and six months and even increased their biomass production. **Implications.** *L. leucocephala* and *G. sepium* showed the best establishment and highest biomass production, making them a potential alternative for silvopastoral systems. **Conclusions.** It is important to select species adapted to local conditions to optimize the productivity and sustainability of silvopastoral systems.
Key words: Forage tres; dry tropics; *Leucaena leucocephala; Gliricidia sepium; Moringa oleífera.*

RESUMEN

Antecedentes. Los bosques secos tropicales son abundantes en árboles con potencial forrajero. Sin embargo, hay pocos estudios sobre sus características agronómicas dirigidos a su utilización en sistemas silvopastoriles intensivos. **Objetivo**. Evaluar el establecimiento y el crecimiento en altura, diámetro, cobertura de copa y producción de biomasa de tres especies de árboles forrajeros (*Leucaena leucocephala, Gliricidia sepium* y *Moringa oleifera*) bajo los efectos de dos niveles de riego (riego y temporal) y tres niveles de defoliación (25, 50 y 75%), con el fin de obtener información para su manejo agronómico en el trópico seco. **Metodología**. Se utilizó un diseño experimental factorial en bloques al azar. Los resultados se analizaron mediante modelos lineales generales. **Resultados**. Durante el establecimiento, *L. leucocephala* alcanzó una mayor altura y diámetro que *M. oleifera* y *G. sepium*. Luego de un período de monitoreo de 30 meses bajo tratamientos de riego y defoliación, se encontró que *L. leucocephala* fue la especie con mayor crecimiento, pero solo *G. sepium* mostró diferencias significativas entre tratamientos de riego para altura y diámetro. En producción de biomasa, *L. leucocephala* tuvo el mayor rendimiento al 75% de defoliación, con 103.03 ± 16.52 kg MS/ha, seguida de *G. sepium*, también al 75% de defoliación, con 79.62 ± 19.77 kg MS/ha. También se observó que las especies no se vieron afectadas luego de tres podas sucesivas con períodos de recuperación de tres y seis meses e

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incluso incrementaron su producción de biomasa. **Implicaciones**. La *L. leucocephala* y la *G. sepium* presentaron el mejor establecimiento y mayor producción de biomasa, por lo cual se pueden considerar como una alternativa potencial para sistemas silvopastoriles. **Conclusión.** Es importante seleccionar especies adaptadas a las condiciones locales para optimizar la productividad y sostenibilidad de los sistemas silvopastoriles.
Palabras clave: Árboles forrajeros; *Leucaena leucocephala*; *Gliricidia sepium; Moringa oleífera.*

INTRODUCTION

The Tropical Dry Forest (TDF) is one of the largest and most important ecosystems in Mexico and Central America. It exhibits marked seasonality in rainfall distribution, resulting in several months of drought (Murphy *et al.*, 1995; Falconi-Briones *et al.*, 2022). In recent decades, TDFs have suffered significant degradation, primarily because of their transformation into agricultural land or pastureland for extensive livestock farming, leaving only small remnants of original vegetation (Maass *et al.*, 2002).

Plant species in these ecosystems, in addition to being subject to defoliation and browsing, face additional stress that can compromise their development and survival. In this context, the ability to regrow becomes a desirable characteristic, although this varies among species and depends on multiple factors. Among the most relevant are the overall vitality of the plant, its growth potential, and the speed with which it can regenerate its leaf tissue. These elements together determine the level of adaptation and resilience of each species to adverse environmental conditions (González-Gómez *et al.*, 2006; Rusch and Skarpe, 2009).

A large body of research on silvopastoral systems and forage trees in TDF has focused on the use of *Leucaena leucocephala*, due to its remarkable adaptability and high biomass production (Azuara-Morales *et al.*, 2020; Petit *et al.*, 2010; Pérez-Luna *et al.*, 2023). However, other species can also have promising characteristics for integration into these systems. For example, *Gliricidia sepium* is characterized by its rapid growth, reaching maturity in six to eight months, and is notable for its high protein and energy content (Castañeda-Serrano *et al.*, 2023; Cañaveral-Martínez *et al.*, 2025). *Moringa oleifera* has been shown to have a wide range of adaptability, as it can grow in both acidic and alkaline soils, tolerates drought conditions, and can develop from sea level to altitudes of 1,800 meters (Raman *et al.*, 2018). Even though it is not a native species, it has been grown in Mexico for a long time without becoming invasive. Besides, there is increasing interest amongst farmers in cultivating it due to its nutritional and nutraceutical properties (Olson and Fahey, 2011; Islam *et al.*, 2021).

In this sense, diversifying silvopastoral systems through the incorporation of multiple species could provide a wider range of ecological and productive benefits, in addition to increasing the resilience of grazing areas to adverse environmental conditions. Therefore, the objective of this work was to evaluate the establishment, growth, and biomass production of three species of forage trees (*Leucaena leucocephala*, *Gliricidia sepium* and *Moringa oleifera*) under the effects of irrigation and defoliation in order to obtain information for their agronomic management in the dry tropics.

MATERIALS AND METHODS

Study site and seed material

The study was conducted at the INIFAP-Apatzingán Valley Experimental Field, located at 19°24'23.59" N and 102°0'47.91" W, in Michoacán, Western Mexico. The site has an altitude of 300 meters above sea level. The climate is warm semi-arid with average annual temperature of 28°C and average annual rainfall of 800 mm (INAFED, 2010). The soil is classified as a vertisol, characterized by a high content of expansive clay. Native vegetation is dominated by Tropical Deciduous Forest and Tropical Thorny Forest (Mellado-Vázquez *et al.*, 2005).

A plot measuring 0.5 has was ploughed, furrowed and fenced with plastic mesh to prevent rodent entry, and a drip irrigation system was installed. The selected species were *Leucaena leucocephala*, *Gliricidia sepium*, and *Moringa oleifera*. Seeds of *Leucaena leucocephala* var. Cunningham were obtained from Fundación Produce Michoacán, A.C. Seeds of *Gliricidia sepium* were collected from non-cultivated trees within plots under silvopastoral management nearby the Chamela-Cuixmala Biosphere Reserve, Jalisco, Mexico, as part of a wider project on dry tropical forage trees (Sánchez-Romero *et al.*, 2022). Finally, *Moringa oleífera* seeds were obtained from plants used in previous experiments at the study site.

Experimental design

The experiment was divided into two main stages: 1) Establishment, which consisted of the first 180 days, during which all plants were maintained with uniform irrigation to promote their survival and growth. 2) Treatment application (days 180 to 540), during which irrigation and defoliation treatments were applied (at 180, 360, and 450 days).

A factorial experimental design was used in four plots randomly divided into blocks with three factors: 1) Species (3), 2) Irrigation (2), and 3) Defoliation (3).

This resulted in a total of 18 treatments with four replicates (one in each block), each measuring 3 x 5 m, for a total of 15 m2. A density of 40,000 plants/hectare was used, with rows of 1.8 meters and a distance between plants of 15 cm. Ten individuals per replicate were sampled.

Two irrigation levels were evaluated: 1) Rainfed (rainwater plus four hours of irrigation per week) and 2) Rainfed (rainwater only). The difference in soil moisture between the irrigated and rainfed treatments averaged 20%. It is important to mention that the soil had a field capacity of 50% due to its high clay content.

Three defoliation levels were used, corresponding to 25, 50, and 75% of leaves and tender stems. This percentage was determined by measuring each individual and, based on their height and canopy coverage, pruning the proportions for each treatment. Branches were selected from the base, center, and canopy to ensure uniform pruning. Defoliation was carried out in February, August, and November 2016.

Evaluation of soil properties

Before planting, with the experimental units already in place, the first soil sample was taken at time zero. Water-stable aggregates were determined in two sizes: macroaggregates (0.25-1 mm), macroaggregates (>1 mm), and field capacity (Hallett *et al.*, 2009). The pH was determined in a soil-water suspension (1:10) with a potentiometer. Nitrates and ammonium were extracted with 2N KCL and quantified using an autoanalyzer, calculating the total available N as their sum. Orthophosphates were obtained using the Mehlich III extractant (Mehlich, 1984) and were measured colorimetrically with molybdate reduced with ascorbic acid in an autoanalyzer (Technicon Industrial Systems, 1977). The percentage of organic matter was determined using the method of Walkley (1947), based on the oxidation of organic carbon in finely ground soil samples. Below is a diagram of the experimental design (Figure 1).

Statistical analyses

Establishment period. To identify the best species in terms of growth, the data obtained throughout the establishment period were compared using a general linear model (GLM) analysis, in which the response variables were growth in i) height and ii) diameter.

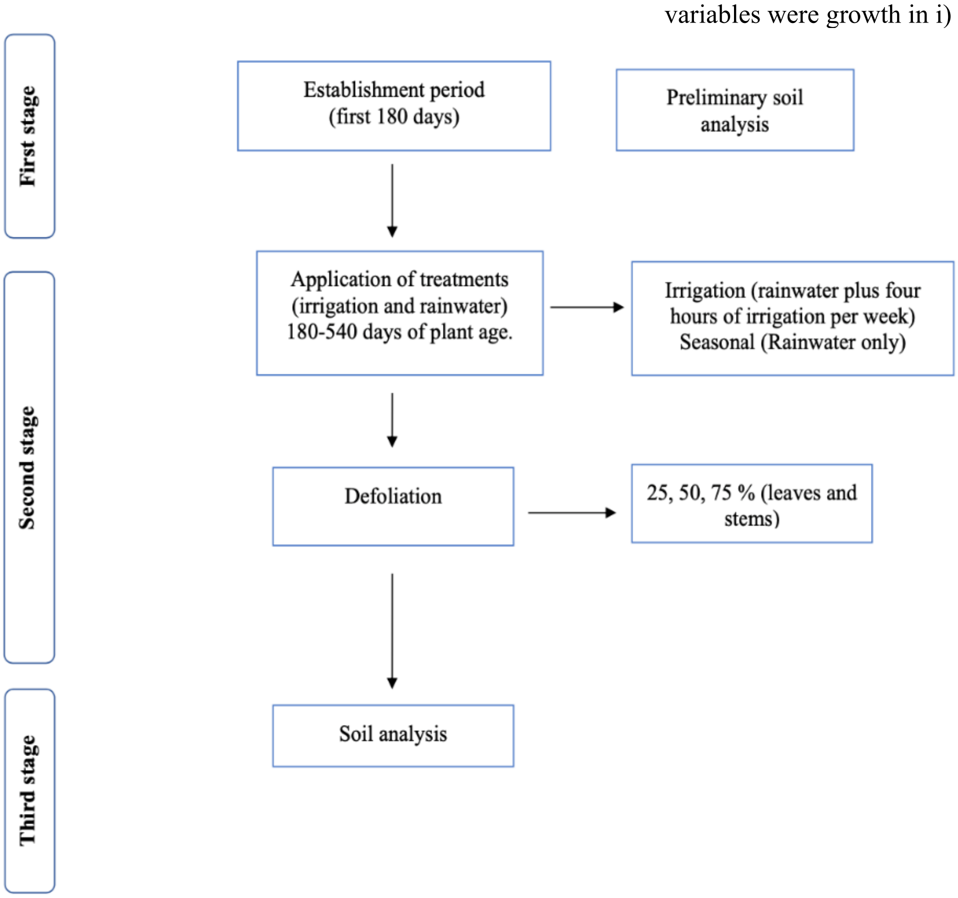

Figure 1. Flowchart of the experiment.

Treatment application: This analysis was used to identify the best treatment within each species, combining irrigation and defoliation. Data obtained between 180 and 540 days after sowing were used. This comparison, like the previous one, was performed using a GLM, and four response variables were used: growth in: i) height, ii) diameter, iii) canopy cover and iv) biomass production.

The fixed variables were irrigation (I), defoliation (D), time (T), and period (P), as well as the interaction between them, with blocks as a random factor. For this analysis, the four response variables were logarithmically transformed to meet the criteria of normality and homoscedasticity (Crawley, 2012). A completely randomized design was used for the evaluation of soil properties.

All statistical analyses were carried out using the lme4 package version 1.0-4 (Pinheiro and Bates, 2000) in the R software version 1.0. 3.1.1, Development Core Team (Pinheiro *et al.*, 2007). Model simplification was based on sequentially removing non-significant fixed terms (factors/interactions) (Crawley, 2012; Pinheiro and Bates, 2000).

RESULTS

During the establishment period, *L. leucocephala* exhibited the greatest height; however, in terms of diameter, *G. sepium* exhibited the best results (Table 1). After a 12-month monitoring period under experimental treatments, the three studied species were generally found to be resistant to drought and defoliation (Table 1). However, there were differences between species, with *L. leucocephala* being superior to *M. oleifera* and *G. sepium* for all the evaluated variables.

When evaluating the effect of irrigation, *L. leucocephala* had higher values than the other evaluated species, with *M. oleifera* showing the lowest values for diameter. However, among the three species, no differences were found between irrigation and rainfed conditions for height and diameter (Table 2). In terms of height, diameter, and biomass, when compared by defoliation level, *L. leucocephala* surpassed *M. oleifera* and *G. sepium*. In *G. sepium*, the best height was obtained at 50% pruning, the highest biomass at 50 and 75%, and in *L. leucocephala* only at 75% for biomass (Table 3). The soil characteristics evaluated did not show any differences according to the type of plant species introduced (Table 4).

DISCUSSION

Establishment period and application of treatments

The results indicate significant differences between species, with *L. leucocephala* showing the greatest growth during the establishment period. This is important because establishment time is an essential parameter when selecting and identifying the best species for silvopastoral systems, as producers prefer easy-to-establish, fast-growing species to start their agronomic management (Anguiano *et al.*, 2012). Although *M. oleifera* showed a moderate growth rate and *G. sepium* even slowed during the evaluation period, both species can be considered suitable for silvopastoral systems since, at the end of the establishment stage, they reached heights between 0.5 and 1.0 meters, which, according to previous studies, is considered sufficient to initiate management practices in silvopastoral systems (Murgueitio *et al.*, 2006).

Table 1. Growth and biomass production after establishment of selected species.

Variable (cm)	Establishment			SEM	*P*<value		
	Leucaena leucocephala	***Gliricidia sepium***	***Moringa oleifera***		**Species**	**Irrigation**	**Defoliation**
Height	58.69^{a}	33.92^{c}	42.12^{b}	0.643	0.001		
Diameter	0.64^{b}	0.76^{a}	0.59^{c}	0.009	0.001		
	Treatment application						
Height	186.35^{a}	74.76^{c}	108.47^{b}	1.477	0.001	0.001	0.001
Diameter	2.01^{a}	1.89^{b}	1.61^{c}	0.018	0.001	0.001	0.001
Canopy cover (cm^2)	6296.5^{a}	4660.5^{b}	2032.8^{c}	124.81	0.001	0.001	0.001
Dry Matter g/kg	226.30^{a}	214.34^{a}	46.90^{b}	10.83	0.001	0.274	0.001
Biomass (kg DM/ha)	75.43	69.08	15.13	3.773	0.001	0.1422	0.001

SEM - Standard error of means. Values within a row followed by different superscript letters are different ($P < 0.05$).

Table 2. Effect of irrigation on height and diameter of selected species.

Variable	Species			SEM	*P*<value
	Leucaena leucocephala	***Gliricidia sepium***	***Moringa oleifera***		
		Height			
Irrigated	144.96^{a}	57.97^{c}	78.73^{b}	2.864	0.001
Rainfed	146.07^{a}	51.66^{c}	82.82^{b}	2.852	0.001
SEM	2.972	1.443	2.986		
P<value	0.829	0.070	0.238		
		Diameter			
Irrigated	1.70^{a}	1.68^{a}	1.21^{b}	0.044	0.001
Rainfed	1.63^{a}	1.58^{a}	1.35^{b}	0.045	0.001
SEM	0.034	0.042	0.046		
P<value	0.254	0.191	0.079		

SEM - Standard error of means. Values within a row followed by different letters are different ($p < 0.05$).

Table 3. Effect of defoliation levels on height, diameter and biomass of selected species.

Species	***Leucaena leucocephala***			***Gliricidia sepium***			***Moringa oleifera***			**SEM**	***P*<value**
Defoliation (%)	**25**	**50**	**75**	**25**	**50**	**75**	**25**	**50**	**75**		
Height (cm)	152.3^{a}	140.7^{a}	143.50^{a}	55.50^{c}	57.90^{c}	51.00^{c}	87.90^{b}	76.70^{b}	74.90^{b}	1.47	0.001
Diameter (cm)	1.69^{a} a	1.67^{a}	1.71^{a}	1.63^{b}	1.60^{b}	1.59^{b}	1.40^{c}	1.24^{c}	1.20^{c}	0.02	0.001
Biomass (kg DM/ha)	54.70^{a}	68.60^{a}	103.00^{a}	53.50^{a}	74.90^{a}	79.62^{a}	15.35^{b}	12.71^{b}	18.45^{b}	1.76	0.001

SEM - Standard error of means. Values within a row followed by different letters are different ($p < 0.05$).

Table 4. Effect of selected forage species on the physical, chemical and biological properties of the soil.

Variable	**Before establishment**	**Species**			**SEM**	***P*<value**
		Leucaena leucocephala	***Gliricidia sepium***	***Moringa oleifera***		
Macroaggregates >1 mm	1.12	1.98	1.27	1.62	0.28	0.643
Macroaggregates 0.25-1 mm	19.08	20.23	23.99	20.11	4.80	0.236
pH	8.50	8.40	8.42	8.40	0.20	0.678
Ammonium (mg NH_4^+ g^{-1})	3.85	4.02	4.26	4.16	1.10	0.789
Nitrites (mg NO_3 g^{-1})	5.43	4.48	4.78	4.96	1.40	0.768
Total Nitrogen (mg N g^{-1})	9.28	8.50	9.04	9.12	1.50	0.785
Ortophosphates (mg PO_4^- g^{-1})	5.34	5.74	5.77	5.34	0.24	0.742
Organic matter %	1.18	1.20	1.26	1.21	0.20	0.687
Field capacity %	37.84	36.56	36.52	35.99	2.40	0.897

SEM - Standard error of means. Values within a row followed by different letters are different ($p < 0.05$).

The three species studied under these two factors (defoliation and irrigation) were found to withstand high levels of pruning under rainfed conditions and recovery times of three and six months. It has been mentioned that the recovery time between prunings or browsing is of great importance, having a greater effect on biomass yield than height (Nelson *et al.*, 2024). Other studies evaluating recovery times for *L. leucocephala* and *G. sepium* mention that at least five months are required after the first pruning, but only three after the second one. They also mention that pruning is ideal during the dry season, since carbohydrate concentrations are higher (Latt *et al.*, 2000). However, *M. oleifera* did not show good biomass production compared to the other species under the evaluated recovery periods. This could be due to the fact that no fertilizer was applied, with the other two species having the advantage of fixing Nitrogen.

Other authors mention that extending pruning time too much can lead to the formation of excessive woody tissue and lead to more height growth than forage production (Ortega-Vargas *et al.*, 2013). Therefore, it is important to determine the precise timing for such management. Similarly, some studies in the humid tropics have even identified that pruning trees at the end of the rainy season increases edible biomass production during the dry months (Ortega-Vargas *et al.*, 2013), thus preventing them from allocating their resources to flowering and reproduction, instead concentrating solely on edible biomass.

Defoliation

It was observed that biomass production increased with successive pruning in all three species. *L. leucocephala* had the highest biomass production, closely followed by *G. sepium*, obtaining a total of 226.29 and 208.05 kg DM/ha per year, respectively, as the total sum of the three harvests and the different pruning levels. The yields obtained appear to be low when compared to a study on *L. leucocephala* for different pruning intensities. This could be due to plant age, management, or even the harvest season and environmental conditions (Bacab *et al.*, 2012; Tzec-Gamboa *et al.*, 2023). However, increased defoliation did not affect plant recovery and even increased biomass production.

M. oleifera was significantly lower in this regard, with only 46.51 kg DM/year. In silvopastoral systems, biomass production is one of the most important factors, so under the local conditions, the use of this species would be ruled out. However, *M. oleifera* is an important source of animal feed due to its high protein and vitamin content (Cañaveral-Martínez *et al.*, 2025). It has even been recommended in silvopastoral systems due to its rapid growth and high protein content (Jose and Dollinger, 2019). It is important to note that *M. oleifera* is drought-resistant, but under water stress conditions, it is unproductive and even loses its foliage (López-Merlín *et al.*, 2003; Rivas *et al.*, 2013).

The results obtained in the present study for species such as *L. leucocephala* and *M. oleifera* show lower biomass production than that reported by other authors. However, this difference can be attributed to the strong influence of local environmental conditions on the development and productivity of forage species, as previously documented (Hernández-Melchor *et al.*, 2023; Tzec-Gamboa *et al.*, 2023). In our study, low values for soil organic matter and the absence of fertilization could have contributed to the obtained results.

Soil characteristics

The results show that the incorporation of *L. leucocephala, G. sepium, and M. oleifera* did not generate significant differences ($p > 0.05$) in the physicochemical properties of the soil compared to the initial conditions. However, trends were observed that allow for the interpretation of possible medium-term effects. The initial pH decreased slightly in the forage treatments, which could be attributed to the release of organic compounds during the decomposition of plant biomass (Bünemann *et al.*, 2018).

In relation to nitrogen dynamics, ammonium and nitrite concentrations showed increases compared to the soil before the incorporation of forage species (NH_4^+: 3.85 vs. 4.02–4.26 mg/kg; NO_2^-: 5.43 vs. 4.48–4.96 mg/kg), which is consistent with the potential of legumes (*L. leucocephala* and *G. sepium*) to fix atmospheric N and with the mineralization of organic compounds derived from plant residues (Peoples *et al.*, 1995; Kebede, 2021). Likewise, total nitrogen presented values similar to the initial ones (8.5–9.12 mg/kg), indicating that the contributions of the species not only contribute to the availability of inorganic N, but also to the retention of organic N in the soil. Similarly, organic matter content increased slightly compared to the initial condition (1.18% vs. 1.20–1.26%), suggesting that the incorporation of leaf and root residues is favoring the entry of edaphic carbon, although the changes detected are still in the early stages. This behavior is consistent with reports from silvopastoral systems, where the recycling of plant biomass and associated microbial activity tend to improve soil quality over time (Nair *et al.*, 2010).

Overall, the results suggest that, although the changes are not statistically significant in the short term, the integration of forage species into silvopastoral systems could gradually improve nutrient availability and soil stability, contributing to their long-term sustainability.

CONCLUSIONS

The study showed clear differences between forage species: *L. leucocephal*a showed the best establishment and highest biomass production, establishing itself as the species with the greatest potential for silvopastoral systems. *G. sepium* showed good adaptation and tolerance to defoliation, while *M. oleifera*, although with lower yield, remains a complementary alternative due to its high nutritional value.

Successive pruning favored biomass production, with the frequency and timing of management being key factors. Although no significant changes were detected in the soil, positive trends were observed in nitrogen dynamics, suggesting medium-term benefits.

Overall, the results underscore the importance of selecting species adapted to local conditions to optimize the productivity and sustainability of silvopastoral systems.

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Data availability statement. Datasets are available from the authors on request.

Compliance with ethical standards. Due to the nature of this work, this research did not require approval from an ethics committee.

Author contribution statement. F.P. García-Vargas – Conceptualization, methodology, investigation, data curtaion, writing – original draft. **L.E. Robles-Jiménez** – Data curation, formal analysis, writing – original draft, writing – review and editing. **D. Val-Arreola** – Conceptualization, methodology, supervision. **M. Gavito-Pardo** - Conceptualization, methodology, supervision. **L. López-Toledo** - Conceptualization, methodology, supervision. **C.E. González-Esquivel** Conceptualization, methodology, investigation, writing- original draft, writing – review and editing.

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