UNIVERSIDAD AUTÓNOMA CHAPINGO

Unidad Regional Universitaria de Zonas Áridas

Doctorado en Ciencias en Recursos Naturales y
Medio Ambiente en Zonas Áridas

# LA HIGUERILLA (*Ricinus communis* L.) UN CULTIVO ALTERNATIVO PARA LA PRODUCCIÓN DE BIODIESEL EN ZONAS ÁRIDAS

**TESIS**

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EN ZONAS ÁRIDAS

**Presenta:**

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La presente tesis de Doctorado titulada **"La higuerilla (*Ricinus communis* L.) un cultivo alternativo para la producción de biodiesel en zonas áridas"** fue realizada por la **M.C. Mali Nay Buendía Tamariz,** bajo la dirección del **Dr. Ricardo Trejo Calzada y co-dirección del Dr. Ignacio Sánchez Cohen,** ha sido revisada y Aprobada por el Comité Asesor como requisito parcial para obtener el grado de:

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(Pablo Neruda).

# DEDICATORIA

Para Ania Ximena, espero que esto le sirva como inspiración.

## DATOS BIOGRÁFICOS

El presente trabajo fue realizado por Mali Nay Buendia Tamariz, Ingeniero Agrónomo en Sistemas Pecuarios de Zonas Áridas, título obtenido en la Unidad Regional Universitaria de Zonas Áridas (URUZA) departamento perteneciente a la Universidad Autónoma Chapingo, generación 2000-2005.

Durante el periodo comprendido del 2005 al 2011 se desempeñó profesionalmente en la empresa Tyson de México, ocupando cargos de supervisor de crianza de reproductora pesada y supervisor de pollo de engorda.

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Efecto de la suplementación de B-caroteno sobre la actividad ovárica y patrón de secreción de la hormona luteinizante en cabras bajo fotoperiodo creciente. ***Revista Chapingo Serie Zonas Áridas.*** 8(2):169-175 2009.

Relación entre la época de empadre y la expresión del peso al nacimiento en caprinos. ***Revista Chapingo Serie Zonas Áridas.*** 9(2):185-191 2010.

Aminoácidos excitadores, fotoperiodos crecientes, y niveles séricos de testosterona en machos caprinos. ***Revista Chapingo Serie Zonas Áridas.*** 9(2):193-200 2010.

Characterization of Biodiesel Produced from Chicken Fat and Pennycress Oil using Different Concentrations of Basic Catalysts. ***Journal of Agriculture and Environmental Sciences***, *4*(1), 127-133 2015. DOI: 10.15640/jaes.v4n1a16

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**Análisis de crecimiento de dos variedades de higuerilla en la Comarca Lagunera, México.** ***XXIX Semana Internacional de Agronomía.*** UJED-FAZ. Gómez Palacio, Durango. México. Septiembre, 2017, pp. 863-869 2017.

## RESUMEN GENERAL

## LA HIGUERILLA (*Ricinus communis* L.) UN CULTIVO ALTERNATIVO PARA LA PRODUCCIÓN DE BIODIESEL EN ZONAS ÁRIDAS

La higuerilla (*Ricinus comunnis* L) es una planta que se caracteriza por un alto contenido de aceite en su semilla, el cual tiene una gran versatilidad en la industria. Además, es una planta que tiene la capacidad de crecer en muchos tipos de climas. Bajo esta premisa, toma importancia como cultivo alternativo para la producción de biodiesel para aminorar los efectos del cambio climático. El objetivo de este trabajo fue evaluar variedades de higuerilla en términos de rendimiento y eficiencia de uso de para la producción de biodiesel en zonas áridas. Se llevaron a cabo experimentos en dos años. En el primero se estableció un experimento en un diseño de bloques al azar con arreglo de parcelas divididas con cuatro repeticiones y con tres densidades de población: 13,888, 9,259 y 6,944 plantas $ha^{-1}$. Las variedades de higuerilla utilizadas fueron Cedaso, Treinta y seis, Rincon y Krishna. El segundo experimento se estableció en un diseño de bloques al azar con cuatro repeticiones y con una densidad de población de 13,888 plantas $ha^{-1.}$ Las variedades usadas fueron Krishna y Rincon. Además, se utilizaron tres tratamientos de humedad del suelo: Alta 0.05 MPa, media 0.31 MPa y baja 0.91 MPa. Las variables medidas fueron velocidad de germinación, altura de planta (HP), días hasta la floración del 50 % de las plantas (DF), área de la hoja (LA), peso seco (DW), tasa de crecimiento relativo (TRC), tasa asimilación neta (TAN), tasa fotosintética, relación fuente-sumidero, índice de cosecha (HI) y rendimiento de semilla, rendimiento de aceite, productividad del agua, valor acido, índice de saponificación e índice de peróxidos. Los datos se examinaron mediante un análisis de varianza y prueba de medias (HSD a $\alpha = 0.05$) y análisis de regresión. Los datos mostraron diferencias significativas entre tratamientos en el rendimiento de semillas, alcanzando rendimientos de hasta 5,200 kg $ha^{-1}$. La variedad Krishna en baja humedad del suelo y en densidades de población altas, fue la que mostró las mejores características agronómicas y de desarrollo para su cultivo en la región árida de la Comarca Lagunera en México con una productividad del agua de 1.41 kg de semilla $m^{-3}$ y 0.66 kg de aceite $m^{-3}$ y un ahorro de hasta 2,900 $m^3$ de agua por hectárea sin afectar la productividad del cultivo.



**Palabras clave:** *Ricinus communis* L., rendimiento de semilla, humedad del suelo.



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**CASTOR BEAN (*Ricinus communis* L.) AN ALTERNATIVE CROP FOR BIODIESEL PRODUCTION IN ARID LANDS**


## ABSTRACT

The castor bean (*Ricinus comunnis* L) is a plant that is characterized by a high content of oil in its seed, which has great versatility in the industry. In addition, it is a plant that can grow in many types of climates. Under this premise becomes important as an alternative crop to produce biodiesel to lessen the effects of climate change. The objective of this work was to evaluate castor bean varieties in terms of yield and efficiency of water use to produce biodiesel in arid zones. Experiments were carried out during two years. The first one, was established in a random block design with split plots arrangement and four replicates and three population densities: 13,888, 9,259 and 6,944 plants $ha^{-1}$. The castor varieties used were Cedaso, Treinta y seis, Rincon and Krishna. The second experiment was established under a randomized block design with four replicates and a population density of 13,888 plants $ha^{-1}$. The varieties used were Krishna and Rincon. In addition, three soil moisture treatments were used: High 0.05 MPa, medium 0.31 MPa and low 0.91 MPa. The variables measured were speed of germination, height of plant (HP), days until flowering of 50 % of the plants (DF), leaf area (LA), dry weight (DW), relative growth rate (RGR), net assimilation rate (NAR), photosynthetic rate, source-sink relationship, harvest index (HI), seed yield, oil yield, water productivity, acid value, peroxide value and saponification value. The data were examined by variance and means tests (HSD at $\alpha = 0.05$) and regression analysis. The data showed significant differences between treatments in seed yield, reaching yields of up to 5,200 kg $ha^{-1}$. The Krishna variety in low soil moisture and high population densities was the one that showed the best agronomic and development characteristics for its cultivation in the arid region of the Comarca Lagunera in Mexico with a water productivity of 1.41 kg of seeds $m^{-3}$ and 0.66 kg of oil $m^{-3}$ and saving of water of up to 2,900 $m^3$ per hectare without affecting crop productivity.



**Key words:** *Ricinus communis* L., seeds yield, soil moisture.



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# CAPÍTULO I

## 1. PRESENTACIÓN

El consumo de energía es un hecho esencial en la historia de la humanidad, en especial si ésta se enfoca desde un punto de vista económico o ambiental. Las dos grandes revoluciones económicas de la humanidad, la revolución agrícola del neolítico y la revolución industrial del siglo XVIII que dieron origen a las sociedades agrícola e industrial, respectivamente, fueron básicamente revoluciones energéticas. Ambas consistieron en la introducción de determinados convertidores de energía que multiplicaron la energía disponible por persona, lo cual propició que se ampliara la productividad del trabajo y, por consiguiente, se incrementara el nivel de vida de las personas de forma significativa (Cipolla, 1994).

En este sentido, son amplias las razones por las cuales el petróleo debe ser reemplazado por una fuente alternativa y sostenible de energía, y que pueda ser usada como materia prima industrial en el futuro cercano. Bajo este panorama, las fuentes de energías renovables, como la biomasa vegetal, se presentan como una de estas opciones y se han encontrado diversas especies que tienen potencial para la producción de biocombustibles. Una de ellas es la higuerilla (*Ricinus communis* L.), planta oleaginosa que se encuentra ampliamente distribuida en México (Solís *et al.*, 2016).

El aceite de higuerilla, producido a partir de semillas de higuerilla, es un producto prometedor para los próximos años que tiene una gran variedad de aplicaciones, particularmente como una fuente de energía renovable (Patel *et al.*, 2016). La higuerilla es un cultivo con creciente importancia económica en Brasil debido a su uso en la industria química y farmacéutica y principalmente, como un sustituto del diésel en la producción de biocombustibles; además, se ha cultivado principalmente en zonas áridas de ese país (Sausen *et al.*, 2010).

En México, existe interés en validar la higuerilla (*Ricinus communis* L.) en siembras comerciales (Ocampo *et al.*, 2015). A pesar de ello, en gran parte del país carece de recomendaciones para su cultivo, uso de la planta y sus residuos (Domínguez *et al.*, 2015). De hecho, aún son insuficientes los estudios sobre el comportamiento agronómico y las características del crecimiento y desarrollo de diversos genotipos, particularmente en las zonas áridas.

Por otra parte, las zonas áridas representan una de las opciones de mayor viabilidad para responder en gran medida a los retos del siglo XXI en términos sociales, ambientales y económicos, debido a su extensión territorial y la abundancia y diversidad de sus recursos naturales, lo cual hace posible que de manera integral puedan desarrollarse tecnologías que ayuden en la mitigación de los impactos del uso de fuentes de energía fósil.

La estructura del presente documento inicia con el capítulo II donde se realiza un análisis de variedades y densidades de población sobre el rendimiento de cuatro variedades de higuerilla como especie alternativa para la producción de biodiesel. Posteriormente, en el capítulo III se analiza la producción de las dos mejores variedades en cuanto al rendimiento de semilla sometidas a diferentes contenidos de humedad en el suelo, basados en las variedades usadas en el capítulo II. Finalmente, en el capítulo IV se analiza el desempeño fotosintético y la eficiencia del uso de agua de las dos variedades evaluadas en el capítulo II en diferentes contenidos de humedad en el suelo.

# 2. OBJETIVOS

## 2.1 Objetivo general

- Evaluar diferentes variedades de higuerilla en términos de rendimiento y eficiencia de uso de agua para la producción de biodiesel en zonas áridas.

## 2.2 Objetivos específicos

- Cuantificar la productividad de cuatro variedades de higuerilla para la producción de biodiesel en zonas áridas.
- Evaluar el efecto de la humedad del suelo sobre el rendimiento de semilla en variedades de higuerilla en zonas áridas.
- Medir la influencia de la humedad del suelo sobre la actividad fotosintética y su impacto sobre el rendimiento de aceite en variedades de higuerilla en zonas áridas.
- 

# 3. HIPÓTESIS

La higuerilla (*Ricinus communis* L.) es un cultivo que puede ser producido en zonas áridas con alta productividad del agua.

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# CAPÍTULO II

## Growth and Yield of Castor Oil Bean Varieties in a Dry Land of México

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### ABSTRACT

The aim of this work was to evaluate the productive potential of four varieties of castor oil plants for biodiesel production in a dry land of Mexico, the Comarca Lagunera. The experiment was set up in a randomized block design with split plot plots arrangement and three replicates. The large plot was the variety and the small plot was the population density. The varieties of castor oil plants used were Rincon, Cedaso, Treinta y seis and Krishna. Population densities were 13,888, 9,259 and 6,944 plants ha$^{-1}$, with beds of 1.20 m width and distances between plants of 0.60, 0.90 and 1.20 m, respectively. The variables measured were germination speed index, days at flowering (DAF), plant height (PH), stem diameter (SD), dry weight (DW), leaf area (LA), net assimilation rate (NAR), relative growth rate (RGR), and seed yield (SY). Data were analyzed by analysis of variance, Tukey comparison test (HSD) and a regression analysis (HSD at $\alpha$ = 0.05). The data showed significant differences in the seed yield of castor plants varieties, reaching yields up to 945 kg ha$^{-1}$ in a single harvest. Krishna variety showed the best developmental and agronomic characteristics for cultivation in the arid region of Comarca Lagunera in Mexico.

**Key words:** *Ricinus communis***,** population density, seed yield, arid lands, biofuels.

## INTRODUCTION

The need to reduce the negative effects of greenhouse gas emissions has led to the search for new sources of energy. One of them is plant biomass and several species have been found to have potential for the production of biofuels. One of these species is the castor plant (*Ricinus communis* L.), an oleaginous plant that is widely distributed in Mexico (Solís *et al*., 2016).

Castor plant has enormous potential in the future as an industrial oilseed crop because of its high oil content in the seeds (more than 480 g $kg^{-1}$), the composition of single fatty acids (900 g $kg^{-1}$ of ricinoleic acid) (Gokdogan *et al*., 2015), potential high oil yields (1250-2500 L $ha^{-1}$), and the ability to grow under conditions of drought and salinity (Severino *et al*., 2012).

Castor oil plant is a $C_3$ plant of the *Euphorbiaceae* family, it is a monotypic species that consists of 22 subspecies, as well as a considerable number of cultivars created by plant breeders (Webster, 1994). This species shows a wide phenotypic diversity with variations in growth habits, color of the leaves, stem and seeds and oil content (Savy Filho *et al*., 2007). In addition, it presents variation in the size of the plant cycle duration (annual or perennial), appearance and biometric parameters of seeds (Chan *et al*., 2010). The castor plant differs greatly about its growth and appearance. There is variation in the habit of growth, foliage color, stems, size and color of the seed and oil content, so that the varieties usually have little similarity to each other (Salihu *et al*., 2014).

Actually, *R*. *comunnis* is now revived as an agricultural solution, addressing the need for commercial crops with low input costs and viable returns. In addition, castor oil plant is a hardy crop, easy to establish on the field, resistant to drought, tolerate different types of soil, even marginal soil (Salihu *et al*., 2014). The oil is important to many industrial applications, compared to other vegetable oil, because of its unique ability to withstand high and low temperatures (Mutlu and

Meier, 2010). In addition, for maximum oil yield, the plant needs an environment with a temperature between 19 and 29 °C low humidity throughout the growing season, and soils that are deep, moderately fertile, slightly acidic, well drained, and sandy loams, conditions that can be found in the arid lands (Mubofu, 2016).

In Mexico, castor plant production is mainly focused on herbal medicine, with very little seed production and therefore castor oil. In addition, the castor plant is often considered as a weed. This is one of the reasons why its exploitation is not widespread in the country. At present there are no precise data on the area planted with castor oil or levels of seed production or oil yield, mainly because in our country is not considered a crop but rather a weed (Armendáriz, 2012). However, there is a lot of interest in promoting its cultivation as an alternative for biofuel production.

Although the castor plant is a cosmopolitan species with good adaptability and rusticity, it is important that its cultivation be carried out by implementing the same activities that are carried out in any other crop of agricultural interest. Also, there are still some components in handling and choice of varieties that require to be strengthen to secure optimal use especially in arid regions, particularly in arid areas of Mexico. The aim of this study was to evaluate the productive potential of four varieties of castor oil plants in an arid region of northern Mexico.

## MATERIALS AND METHODS

This study was carried out at the Experimental Field of the Regional Unit of Dry Lands (Unidad Regional Universitaria de Zonas Áridas; URUZA). This facility belongs to the Autonomous University of Chapingo (UACh), Mexico, and is located at 25°53' N, 103°36' W and an elevation of 1,117 meters above sea level in a region known as Comarca Lagunera. This region has a very dry climate with summer rains, an average annual rainfall of 270 mm, with a thermal oscillation from 10 to 29 °C (CONAGUA, 2019).

**Experimental design.** An experiment was set up in a randomized block design in split plot arrangement with three replications. The large plot was the variety and the small plot was population density. Four varieties of castor oil plants were used: Rincon, Cedaso, Treinta y seis and Krishna. The population densities were 13,888, 9,259 and 6,944 plants $ha^{-1}$, which corresponds to seedbeds of 1.20 m wide and separation of 0.60, 0.90 and 1.20 m between plants, respectively. The experimental unit consisted of three seedbeds 7 m long and 1.2 m wide, while useful plot corresponded to the 5 central meters from the central seedbed.

**Establishment of experiment and irrigation system**. The experiment was conducted from June to December of 2015. The varieties of castor oil plants were placed in germination trays filled with peat moss. The trays were placed in a greenhouse and maintained in a moist condition. Once the plants reached 10 to 15 cm in height, were transplanted into the field. A drip irrigation system was established with water drawn from a deep well. After transplantation, watering was performed every 8 days until the end of the experiment. The water flow that reached the plot was 0.75 liters per hour; the irrigation time used was 5 hours. The total applied irrigation lamina was 41.5 cm.

**Measured variables.** The variables measured were germination speed index, days at flowering (DAF), date when 50 % of the population shows the first flower; plant height (PH), dry weight (DW), leaf area (LA), stem diameter (SD), net assimilation rate (NAR), relative growth rate (RGR), and seed yield (SY). The variables of fresh and dry matter were evaluated selecting and identifying plants at random within each treatment at the end of the experiment; and the seed yield variable (kg $ha^{-1}$) was evaluated by considering the seeds of the fruits of the useful plot. The germination speed (GS) was calculated by the expression proposed by Maguire (1962) as follows:

$$GS = \sum N_t / T \quad (1)$$

Where: $N_t$ = is the cumulative proportion germinating at each sampling time, and T number of days elapsed since the start of the trial.

With the values of leaf area and dry weight, the NAR (g $cm^{-2}$ $d^{-1}$) was calculated using the following equation:

$$NAR = \frac{(\mathrm{W2} - \mathrm{W1})(\ln \mathrm{LA2} - \ln \mathrm{LA1})}{(\mathrm{T2} - \mathrm{T1})\,(\mathrm{LA2} - \mathrm{LA1})} \quad (2)$$

Where: ln = natural logarithm, LA1, 2 = leaf area at the beginning and end of the time interval, w1, 2 = dry weight at the beginning and end of the time interval, T1, 2 = initial and final time interval.

Also, with DW data the RGR (g $g^{-1}$ $d^{-1}$) was calculated with the following equation:

$$RGR = \frac{(\ln \mathrm{W2} - \ln \mathrm{W1})}{(\mathrm{T2} - \mathrm{T1})} \quad (3)$$

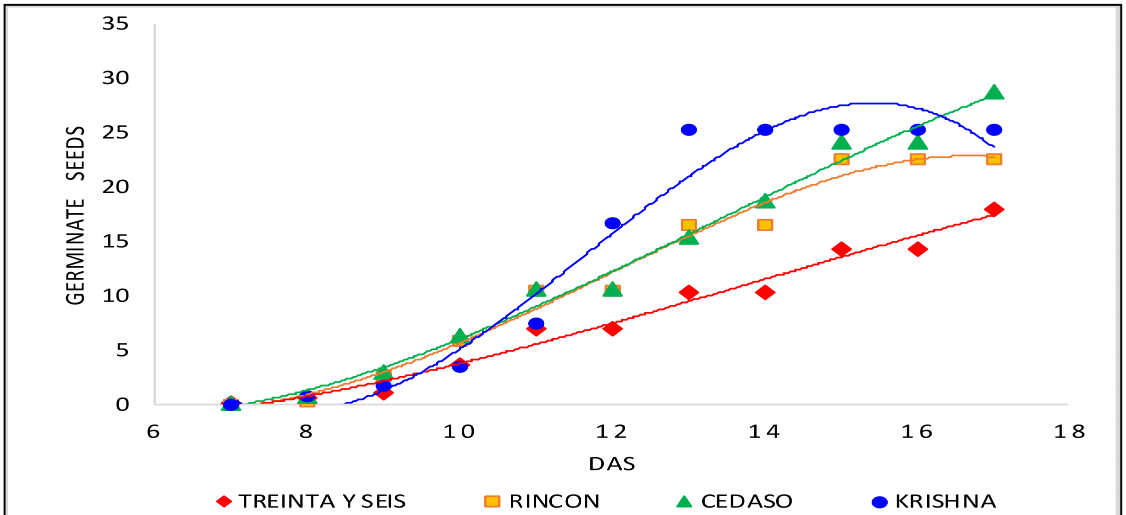
Where: ln = natural logarithm, W1, 2 dry weight at the beginning and end of the time interval, T1, 2 = initial and final time interval.

**Data analysis.** To interpret the quantitative variables, an analysis of variance was applied and, in those cases in which there were significant differences between the treatments, the Tukey comparison test (HSD) was used on days to flowering and seed yield variables. In addition, a multivariate analysis of variance (MANOVA) was performed in repeated measures and regression analysis in variables of leaf area, dry weight. Mauchly's sphericity test indicates that the spherical assumption for the leaf area and dry weight variables was violated. In both variables, it will be used for the significance of the study factors of the F calculated from the Greenhouse-Geiser Epsilon (G-G). Effect size measures ($\eta^2$

and $R^2$) are presented for the analyses. Statistical analysis was performed using SAS software version 9.0.

## RESULTS AND DISCUSSION

The analysis of the emergency speed indicates that there were no significant differences between varieties. The Krishna variety presented the fastest emergence with an emergency speed of 2.1. The other varieties presented a lower emergence speed, for the case of the Cedaso and Rincon varieties it was 1.9 in both, the variety Treinta y seis presented the lowest velocity of emergence, and it was 1.4. In Figure 1, the accumulative germination rate is presented, where it can be seen that the Krishna variety is the one with the highest germination speed.




| | |
|---|---|
| Treinta y seis<br>y = 50/(1 + 1.68E+02*e^(-0.26 X))<br>$R^2$= 0.975 | Cedaso<br>y = 37.3/(1 + 3.53E+02*e^(-0.42 X))<br>$R^2$= 0.989 |
| Rincon<br>y = 39/(1 + (1.98E+02*e^(-0.35 X))<br>$R^2$= 0.974 | Krishna<br>y = 25.4/(1 + 4.18E+02*e^(-0.86 X))<br>$R^2$= 0.988 |

**Figure 1.** Accumulated germination of castor oil seeds from four varieties: Cedaso, Krishna, Rincon and Treinta y Seis, in the Comarca Lagunera, Mexico.

The seeds of *R. communis* L. show high percentage of germination across a range of temperatures (20–35 °C), also, possesses a high degree of thermo-plasticity with faster germination at higher temperatures (Ribeiro *et al*., 2015).This is very appropriate for a species that grow in severe environmental conditions, such as the arid and semi-arid zones. Therefore, the rapid emergency of the seeds of the Krishna variety is a favorable feature especially in those hostile environments, where they need to grow quickly and make the most of the available resources.

According to the results for days at flowering (DAF), significant differences were observed (HSD at $\alpha = 0.05$) among treatments. In general, Cedaso variety showed more rapid blooms, independently of the population density as compared to the other varieties. However, Krishna variety at the highest and lowest population densities showed statistically similar DAF to Cedaso variety. In addition, in all varieties, the faster flowering occurred at the lower population densities (Table 1).

**Table 1.** Days at flowering of four castor oil plants varieties (Cedaso, Rincon, Krishna y Treinta y Seis), in three population densities in the Comarca Lagunera, México.

| VARIETY | POPULATION DENSITY (plants ha$^{-1}$) | DAYS AT FLOWERING (days after sowing) |
|---|---|---|
| CEDASO | 13888 | 49 ab |
| | 9259 | 47 a |
| | 6944 | 47 a |
| KRISHNA | 13888 | 54.3 abc |
| | 9259 | 56.3 bcd |
| | 6944 | 54 abc |
| RINCON | 13888 | 74 f |
| | 9259 | 64.3 de |
| | 6944 | 63 cde |
| TREINTA Y SEIS | 13888 | 64.3 de |
| | 9259 | 70 ef |
| | 6944 | 63 cde |

Different letters among columns indicate significant differences (HSD at $\alpha = 0.05$).

Differences in DAF are probably due to the variability of the genotypes used in this study. About this, Vwioko and Fashemi (2005) reported blooming of castor plant at 96 days after sowing (DAS), while in our study bloom occurred earlier. Zamora *et al.* (2011) define those varieties with less than 100 days to harvest as early and intermediate those with 110 days to harvest. On the other hand, Rico *et al*. (2011) mention that an early variety is one that harvest cycle is 120 days and an intermediate or late to 150 days. Therefore, Cedaso variety could be an early variety and the other varieties in this study fall within the range of intermediate, which could explain the differences among the beginning of flowering.

Regarding the height of the plant, differences between treatments were observed during the period evaluated. The lower population density was the one that favored greater heights in all varieties, and when the population density increased the PH decreased. Also, independently of the density of population, the variety

Krishna was the one that presented the greater heights and the Cedaso variety the one of smaller height. (Table 2).

**Table 2.** Plant height of four castor oil plants varieties (Cedaso, Rincon, Krishna y Treinta y Seis), in three population density, in the Comarca Lagunera, México.

| VARIETY | POPULATION DENSITY (plants $ha^{-1}$) | PLANT HEIGHT (cm) (days after sowing) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 71 | 85 | 99 | 113 | 127 | 141 | 152 |
| CEDASO | 13888 | 40 a | 48 b | 56 b | 62 c | 70 d | 78 d | 81 d |
| | 9259 | 37 a | 50 b | 63 b | 82 bc | 88 cd | 97 cd | 102 cd |
| | 6944 | 46 a | 58 ab | 69 b | 83 bc | 100 bc | 112 abcd | 116 abcd |
| KRISHNA | 13888 | 34 a | 55 ab | 76 ab | 99 ab | 122 abc | 141 abc | 145 abc |
| | 9259 | 39 a | 59 ab | 78 ab | 107 ab | 130 ab | 147 ab | 153 ab |
| | 6944 | 48 a | 76 a | 103 a | 132 a | 146 a | 160 a | 164 a |
| RINCON | 13888 | 39 a | 46 b | 53 b | 69 c | 90 bcd | 108 bcd | 111 bcd |
| | 9259 | 42 a | 53 b | 63 b | 82 bc | 105 bcd | 131 abc | 132 abc |
| | 6944 | 40 a | 57 ab | 72 ab | 85 bc | 99 bcd | 109 bcd | 111 bcd |
| TREINTA Y SEIS | 13888 | 39 a | 49 b | 58 b | 75 bc | 94 bcd | 109 bcd | 113 bcd |
| | 9259 | 40 a | 54 b | 68 b | 83 bc | 100 bcd | 115 abcd | 120 abcd |
| | 6944 | 47 a | 59 ab | 69 b | 84 bc | 99 bcd | 116 abcd | 120 abcd |

Different letters among columns indicate significant differences (HSD at $\alpha = 0.05$).

The heights reported in the present study may be due to the availability of resources such as water and nutrients, since when plants are exposed to greater competition, it can lead to low productivity and growth. However, there are studies that indicate that a reduction in spaces results in higher plants (Shinde *et al*., 2018; Severino *et al*., 2006) because there is excessive lateral growth which leads to an increase in competition for light which may lead to greater height, nevertheless, it was not observed in our study. Furthermore, it is believed that the plant height will largely depend on genetic factors, because, there are varieties with heights less that have been reported (Priya *et al*. 2018; Kowser, 2018).

Regarding stem diameter, significant differences were found after 127 DAS, where an effect of population density on the stem diameter can be seen. The highest density favored a smaller stem diameter. In general, as the population density decreased, the stem diameter increased (Table 3). The above is in agreement with Bonilla *et al*. (2016) where they reported a tendency in plants of *Ricinus communis* to present larger diameters in plants with greater height.

**Table 3.** Stem diameter of four castor oil plants varieties (Cedaso, Rincon, Krishna y Treinta y Seis), in three population densities, in the Comarca Lagunera, México.

| VARIETY | POPULATION DENSITY (plants ha$^{-1}$) | STEM DIAMETER (cm) (days after sowing) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 71 | 85 | 99 | 113 | 127 | 141 | 152 |
| CEDASO | 13888 | 0.64 a | 1.03 a | 1.69 a | 1.93 a | 2.03 b | 2.1 b | 2.17 b |
| | 9259 | 0.63 a | 1.03 a | 1.99 a | 2.17 a | 2.34 ab | 2.41 ab | 2.52 ab |
| | 6944 | 0.71 a | 1.27 a | 2.2 a | 2.37 a | 2.51 ab | 2.56 ab | 2.61 ab |
| KRISHNA | 13888 | 0.61 a | 0.97 a | 2.09 a | 2.27 a | 2.61 ab | 2.64 ab | 2.77 ab |
| | 9259 | 0.56 a | 1.13 a | 2.14 a | 2.43 a | 2.78 ab | 3.04 ab | 2.93 ab |
| | 6944 | 0.59 a | 1.14 a | 2.48 a | 2.7 a | 3.21 a | 3.26 a | 3.37 a |
| RINCON | 13888 | 0.78 a | 1.09 a | 2.18 a | 2.47 a | 2.85 ab | 3.13 ab | 3.32 ab |
| | 9259 | 0.65 a | 1.11 a | 1.92 a | 2.23 a | 2.58 ab | 2.61 ab | 2.95 ab |
| | 6944 | 0.74 a | 1.35 a | 2.4 a | 2.65 a | 2.9 ab | 2.72 ab | 2.7 ab |
| TREINTA Y SEIS | 13888 | 0.54 a | 1.06 a | 1.77 a | 1.85 a | 2.11 b | 2.26 ab | 2.42 ab |
| | 9259 | 0.62 a | 0.92 a | 1.79 a | 1.98 a | 2.22 ab | 2.44 ab | 2.48 ab |
| | 6944 | 0.49 a | 1.06 a | 2.12 a | 2.3 a | 2.56 ab | 2.74 ab | 2.88 ab |

Different letters among columns indicate significant differences (HSD at $\alpha = 0.05$).

Regarding leaf area, the results showed significant differences in the interaction time*variety (Wilk's Lambda = 0.23, F (8.42), p = 0.0001, GG = 0.7373 p = 0.0001), as well as in time*density (Wilk's Lambda = 0.63, F (2.99), p = 0.03, GG = 0.7373 p = 0.005). However, in the time*variety*density interaction (Wilk's Lambda = 0.45, F (1.83), p = 0.072, GG = 0.7373 p = 0.3412), there were not significant differences (Table 4). In addition, the most adequate model to measure the effects of the factors was the logistic model. According to this model, it was observed that Cedaso variety had a lower leaf area as population density increased. Also, the Rincon and Treinta y seis varieties presented its greater leaf area in medium population densities. On other hand, the Krishna variety tolerated high population densities (Table 5).

**Table 4.** Within group differences for leaf area of four castor oil plants varieties under three population density. Because the sphericity assumption was violated (Mauchly's sphericity test, χ2 = 10.13, *P* = 0.0063), Greenhouse-Geisser-adjusted (G-G adj.) *P* values were used for the within factor.

| | ***SS*** | ***df*** | ***MSS*** | ***F*** | **G-G adj. *p*** | $\eta^2$ |
|---|---|---|---|---|---|---|
| **Time** | 290174258 | 2 | 145087129 | 131.35 | <.0001 | 0.64 |
| **Time*Var** | 72944718.2 | 6 | 12157453 | 11.01 | <.0001 | 0.16 |
| **Time*PD** | 22623812.4 | 4 | 5655953.1 | 5.12 | 0.005 | 0.05 |
| **Time*Var*PD** | 15559480.9 | 12 | 1296623.4 | 1.17 | 0.3412 | 0.03 |
| **Error** | 53019797.6 | 48 | 1104579.1 | | | |

*SS* = sum of squares; *df* = degrees of freedom; *MSS* = mean sum of squares; G-G adj. *P* = probability value; Greenhouse-Geisser Epsilon 0.7373; PD = Population density

**Table 5.** Logistic regression model for leaf area of four castor oil plant varieties under three population densities.

| VARIETY | POLULATION DENSITY (plants $ha^{-1}$) | LEAF ÁREA ($m^2$) n=12 MODEL | $R^2$ |
|---|---|---|---|
| CEDASO | 13888 | LA= 2.53 $10^3$/(1+1.19 $10^3$ * e^ (-0.09x)) | 0.80 |
| | 9259 | LA=4132.4/(1+4311.9 * e^ (-0.094x)) | 0.84 |
| | 6944 | LA=5014.3/(1+1261.7 * e^ (-0.074x)) | 0.79 |
| KRISHNA | 13888 | LA=5779.2/(1+1.11 $10^{99}$ * e^ (-3.71 $10^{00}$ x)) | 0.85 |
| | 9259 | LA= 2802.5/(1+4.8 $10^{55}$ * e^ (-2.1 $10^{00}$ x)) | 0.89 |
| | 6944 | LA=4897.8/(1+2.54 $10^4$ * e^ (-0.13x)) | 0.88 |
| RINCON | 13888 | LA= 2.02 $10^{10}$/(1+1.98 $10^8$ * e^ (-0.029x)) | 0.94 |
| | 9259 | LA=1.36 $10^{11}$/(1+1.02 $10^9$ * e^(-0.029x)) | 0.93 |
| | 6944 | LA=6679.3/(1+595.02 * e^ (-0.067x)) | 0.92 |
| TREINTA Y SEIS | 13888 | LA=4453.04/(1+3.55 $10^6$ * e^ (-0.161x)) | 0.87 |
| | 9259 | LA= -5.53 $10^{10}$/(1+(-1.40 $10^8$) * e^ (-(-0.019x)) | 0.86 |
| | 6944 | LA=5363.3/(1+1.11 $10^{11}$ * e^ (-0.275x)) | 0.90 |

Leaf area is important in crops such as sorghum (da Silva and Lovato, 2008) and corn (Lambert *et al*., 2014) because it is correlated to grain yield. In this study, the largest foliar areas of each variety also showed the highest yields within each variety. These results are consistent with those reported by Warnock *et al*. (2006), but contrasting to those reported by Lambert *et al*. (2014). In addition, when the leaf area in bean is not affected, it allows increase in yield (Polon-Perez *et al*., 2017). Therefore, the results observed in the leaf area are believed to be positively related to seed yield, because the treatments with the highest yields were those with the largest leaf areas.

Similar results were observed for dry weight accumulation with respect to leaf area. Significant differences were found in time*variety interaction (Wilk's Lambda = 0.35, F (5.22), p = 0.0004, GG = 0.6088 p = 0.0028), as well as in time*density interaction (Wilk's Lambda = 0.50, F (4.81), p = 0.0025, GG = 0.6088 p = 0.0001).

However, the time*variety*density interaction (Wilk's Lambda = 0.50, F (1.57), p = 0.1338, GG = 0.6088 p = 0.1161), was not significant (Table 6).

**Table 6.** Within group differences for dry weight of four castor oil plants varieties under three population density. Because the sphericity assumption was violated (Mauchly's sphericity test, $\chi 2$ = 23.67, *P* <0.0001), Greenhouse-Geisser-adjusted (G-G adj.) *P* values were used for the within factor.

| | ***SS*** | ***df*** | ***MSS*** | ***F*** | **G-G adj.*P*** | **η2** |
|---|---|---|---|---|---|---|
| **Time** | 343288.543 | 2 | 171644.271 | 164 | <.0001 | 0.70 |
| **Time*Var** | 33950.6221 | 6 | 5658.437 | 5.41 | <.0028 | 0.07 |
| **Time*PD** | 41781.3175 | 4 | 10445.3294 | 9.98 | <.0002 | 0.09 |
| **Time*Var*PD** | 20380.408 | 12 | 1698.3673 | 1.62 | 0.166 | 0.04 |
| **Error** | 50235.8572 | 48 | 1046.5804 | | | |

*SS* = sum of squares; *df* = degrees of freedom; *MSS* = mean sum of squares; G-G adj. *P* = probability value; Greenhouse-Geisser Epsilon 0.6088; PD = Population density

The logistic regression model to measure the effects of the factors on dry weight indicates that for Cedaso variety, the greater weight is presented under a low population density. This same tendency is found for the Krishna variety.  Rincon and Treinta y seis varieties had a higher dry weight under medium population densities. However, there was a tendency to continue increasing their dry weight, unlike the other varieties within the population densities evaluated (Table 7).

**Table 7.** Logistic regression model for dry weight of four castor oil plant varieties under three population densities.

| VARIETY | POLULATION DENSITY (plants ha$^{-1}$) | DRY WEIGHT (g) n=12 | |
|---|---|---|---|
| | | MODEL | $R^2$ |
| **CEDASO** | 13888 | DW=69.72/(1 + 3286.5*e^(-0.104x)) | 0.82 |
| | 9259 | DW=180.77/(1 + 2.38 $10^{11}$*e^(-0.281x)) | 0.97 |
| | 6944 | DW=214.36/(1 + 1.81 $10^{11}$*e^(-0.27x)) | 0.88 |
| **KRISHNA** | 13888 | DW= 189.25/(1 + 1631.4*e^(-0.083x)) | 0.91 |
| | 9259 | DW=180.5/(1 + 4902*e^(-0.0087x)) | 0.94 |
| | 6944 | DW=331.4/(1 + 3894.1*e^(-0.075x)) | 0.93 |
| **RINCON** | 13888 | DW=312.57/(1 + 231.13*e^(-0.034x)) | 0.93 |
| | 9259 | DW=34.51/(1 + (-4.06 $10^{00}$)*e^(-0.0087x)) | 0.97 |
| | 6944 | DW=186.45/(1 + 2.10 $10^{6}$*e^(-0.158x)) | 0.90 |
| **TREINTA Y SEIS** | 13888 | DW=3.59 $10^{9}$/(1 + 2.78 $10^{9}$*e^(-0.035x)) | 0.98 |
| | 9259 | DW=-17.20/(1 + (-3.64 $10^{00}$)*e^(-0.0081x)) | 0.92 |
| | 6944 | DW=175.69/(1 + 6962.6*e^(-0.079x)) | 0.94 |

The differences in dry weight are believed to obey the differences in leaf area, because as shown in the results the treatments with the higher leaf area also showed the highest accumulated dry weight. This is consistent with results reported in beans (García-Esteva *et al*., 2003; Polon-Perez *et al*., 2017), soybean (Maitree & Toyota, 2017) and sunflower (Aguilar *et al*., 2005).

The net assimilation rate (NAR) as a rate of growth that focuses on increasing dry matter in time and which is a method used mostly to express plant growth. The results in this study showed significant differences (HSD $\alpha = 0.05$). Krishna and Cedaso varieties presented a significant highest net assimilation rates in the period from 61 to 125 DAS. The highest NAR (2, 031.6 mg cm$^{-2}$ d$^{-1}$) was observed in Cedaso variety with a density of 6,944 plants ha$^{-1}$. However, it was statistically similar to the values found for Krishna variety under the different population densities evaluated. In general, there were not significant differences among the other treatments for this period (Table 8).

In this study, the varieties Krishna and Cedaso in densities of 9,259 and 6,944 plants ha$^{-1}$ respectively, showed the best rate of net assimilation. These rates may be due to different factors since, Niinemets and Keenan, (2014), mention that the photosynthetic capacity of a plant is determined by the morphology and physiology of the leaves. The Krishna variety had low number of big leaves while Cedaso variety showed the highest number of leaves. However, these two varieties (Cedaso and Krishna) showed similar total leaf area.

**Table 8.** Net assimilation rate (NAR) and relative growth rate (RGR) in the period of 61-151 DAS of four castor oil plants varieties in three population density cultivated in the region of Comarca Lagunera, México.

| VARIETY | POPULATION DENSITY (plants ha$^{-1}$) | NAR (mg cm$^{-2}$ d$^{-1}$) | RGR (g g$^{-1}$ d$^{-1}$) |
|---|---|---|---|
| | 13888 | 1 157.6 abc | 0.03925 ab |
| KRISHNA | 9259 | 1 906.1 ab | 0.047 a |
| | 6944 | 1 179.8 abc | 0.0455 a |
| | 13888 | 736.7 c | 0.0325 ab |
| RINCON | 9259 | 559 c | 0.03575 ab |
| | 6944 | 930.7 c | 0.03275 ab |
| | 13888 | 1 226.7 abc | 0.022 b |
| CEDASO | 9259 | 1 013.2 bc | 0.03 ab |
| | 6944 | 2 031.6 a | 0.03525 ab |
| | 13888 | 787.4 c | 0.03725 ab |
| TREINTA Y SEIS | 9259 | 563 c | 0.03175 ab |
| | 6944 | 660.5 c | 0.02875 ab |

Different letters among columns indicate significant differences (HSD at α = 0.05).

For the relative growth rate (RGR) it was observed that the varieties presented significant differences. Krishna variety presented the highest RGR (0.047 mg $g^{-1}$ $d^{-1}$) when cultivated under 9,259 plants $ha^{-1}$. However, it was only statistically different to the value of RGR in Cedaso in population density of 13,888 plants $ha^{-1}$ (Table 8). It is convenient to point out that in general the varieties of castor were not affected by the density of sowing on this parameter, this could allow to establish a greater number of plants $ha^{-1}$ and make a better use of the surface.

The differences in RGR in this study may be due in part to the fact that it was observed that the plant of the Krishna variety showed greater heights and a fewer leaves but larger, whereas the Cedaso variety showed smaller heights and a greater number of leaves, that could have been self-shading the plant, limiting its growth and productivity as mentioned by Ascencio (1972). These growth rates could be improved with fertilization as well as the seed yield as Deewan *et al*. (2017) reported increases up to 28 % in the NAR and 7 % in the RGR with soil enrichment by fertilization in maize crop.

In this study, the seed yield of four varieties of castor under different population densities, showed significant differences (HSD $\alpha = 0.05$) while the Krishna variety under high population density presented the highest yield (945 kg $ha^{-1}$) followed by the Rincon and Treinta y seis varieties in medium population density with yields of 726 and 694 kg $ha^{-1}$, respectively. The Rincon and Treinta y seis varieties in low population densities and Cedaso variety in medium population density were statistically different to Krishna variety in high population density (Table 9).

The variety Krishna yielded 122 % more than the best yield of Rincon variety and 136 % more than the best yield of Treinta y seis variety and 152 % more than the best yield of Cedaso variety. Therefore, Krishna may be alternative variety for this region and potential for other arid regions. In addition, in the higher yielding varieties, the high and medium densities resulted in higher yields. The above mentioned is agreement with the findings of de Oliveira *et al*. (2017). Their results indicate that plants cultivated in the smaller spacings showed higher yield compared to the plants grown in larger spacings.

**Table 9.** Seed yield of four castor oil plants varieties (Cedaso, Rincon, Krishna y Treinta y Seis), in three population densities in the Comarca Lagunera, México.

| VARIETY | POPULATION DENSITY (plants ha$^{-1}$) | SEED YIELD (kg ha$^{-1}$) |
|---|---|---|
| KRISHNA | 13 888 | 598.9 ab |
| | 9259 | 455.8 b |
| | 6944 | 622.2 ab |
| RINCON | 13888 | 945.4 a |
| | 9259 | 617.7 ab |
| | 6944 | 580.4 ab |
| CEDASO | 13888 | 682.8 ab |
| | 9259 | 726.8 ab |
| | 6944 | 410.8 b |
| TREINTA Y SEIS | 13888 | 661.9 ab |
| | 9259 | 694.5 ab |
| | 6944 | 377.3 b |

Different letters among columns indicate significant differences (HSD at $\alpha = 0.05$).

Moreover, the highest values obtained for seed yield in each variety can probably be attributed to its greater leaf area and dry weight agreeing with those results reported by Aguilar *et al*. (2005). However, in the case of the Krishna variety, the highest yield can be attributed to the leaf area but not to the dry weight. In addition, the yields obtained were competitive to those reported by Rico *et al*. (2011) since they obtained yields of 900 kg ha$^{-1}$ per cut. In our study, only one single harvest was carried out. González *et al*. (2011) reported yields ranging from 2-4 t ha$^{-1}$ in hybrids and outstanding varieties with recommendations of three or four cuts per year.

## CONCLUSIONS

The results derived from this study indicate that *Ricinus communis* L. can be successfully cultivated in areas of marginal agronomic potential such as arid lands and represents a good option in terms of its use to produce oil which could be used for biodiesel production. Within the varieties studied, Krishna presented the best phenological and agronomic characteristics for its cultivation in arid lands of the Comarca Lagunera, Mexico. Also, it was the most productive in terms of seed yield when considering yields of 945 kg $ha^{-1}$ per cut. In addition, the high and medium population densities evaluated had the best seed yield.

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# CAPÍTULO III

## Castor seed yield at suboptimal moisture soil: It is successful?

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**ABSTRACT**

This study discusses how soil moisture influences the seed yield of two Castor plant varieties in a semiarid zone of Mexico. The experiment was set up in a randomized block design with four replicates. The varieties of castor plants used were Rincon and Krishna, and the population density was 13,888 plants $ha^{-1}$. Three treatments of soil moisture were used: high -0.05 MPa, medium -0.31 MPa and low -0.91 MPa in each variety. The variables measured were height plant (HP), days to flowering of 50 % of the plants (DF), leaf area (LA), dry weight (DW), source-sink relationship, harvest index (HI) and seed yield. Data was analyzed by variance and means tests (HSD at $\alpha = 0.05$) and regression analysis. The data showed significant differences in the seed yield in the treatments, reaching yields of up to 5200 kg $ha^{-1}$. Krishna variety in low soil moisture showed the best developmental and agronomic characteristics for cultivation in the arid region of Comarca Lagunera in Mexico and may be an option for multiple production purposes.

**Key words:** Soil moisture, *Ricinus Communis* L., seed yield.

## INTRODUCTION

Castor plant is a $C_3$ plant of the Euphorbiaceae family (Webster, 1994). This species shows a wide phenotypic diversity with variations in growth habits. It may have different color of leaves, stem and seeds. Also, the plant may differ on size, cycle duration, characteristics of the seeds and oil content (Savy Filho *et al*., 2007; Chan *et al*., 2010).

The largest producers of castor bean seeds are India and Brazil and the main market is in United States of America and United Kingdom (Pius *et al*., 2014). Castor oil produced from castor plant seeds has long been appreciated for having an important commercial value. It has more than 700 industrial uses (Anjani, 2012). Moreover, it is a promising product for a variety of applications in the coming years, particularly as a source of renewable energy (Patel *et al*., 2016). In addition, it has been grown as a source of oil for biofuels production largely in arid areas of Brazil. However, the physiological mechanisms involved in its drought tolerance are not well known (Sausen *et al*., 2016).

In Mexico, there is interest in validating the castor plant (*Ricinus communis* L.) in commercial sowings (Jiménez *et al*., 2015). Despite this, in much of the country there are no recommendations for the cultivation, and use of the plant and its residues (Domínguez *et al*., 2015). Moreover, there are still insufficient studies on the agronomic behavior and characteristics of growth and development of various genotypes, particularly in arid areas. This study discusses how soil moisture influences the seed yield of two Castor plant varieties in a semiarid area of Mexico. It explores the concept that plants with a good amount of soil moisture reveal their best productive performance.

## MATERIALS AND METHODS

An experiment was conducted at the Experimental Field of Unidad Regional Universitaria de Zonas Áridas of Universidad Autónoma Chapingo, Mexico. It is located at 25°53' N, 103°36' W and an elevation of 1,117 meters above sea level in a region known as Comarca Lagunera. This region has a very dry climate with summer rains, an average annual rainfall of 270 mm, with a thermal oscillation from 10 to 29 °C (CONAGUA, 2019).

**Experimental design.** The experiment was set in a randomized block design with four replicates. The sowing date was in June 30, 2016. Two varieties of castor plants were evaluated: Rincon and Krishna. The population density was 13,888 plants $ha^{-1}$, which corresponds to seedbeds with plastic film mulch of 1.20 m wide and separation of 0.60 m between plants. The experimental unit consisted of four seedbeds 9 m long and 1.2 m wide. The useful plot corresponded to the 7 central meters from the two-central seedbeds.

**Establishment of experiment and irrigation system**. The varieties of castor oil plants were manually seeded in the field. A tape-type drip irrigation system was used placing the lines on the soil surface with a controlled operating pressure of 16 PSI. The drip irrigation system was established derived from a main line pipe and side connections of PVC for each plot. The drip irrigation system was controlled by a stopcock that allowed the delivery of water according to the program of irrigation with water drawn from a deep well. After seeding and once the plants reached 15 to 20 cm in height (at 39 day after sowing, DAS), an initial watering was applied to reach soil field capacity. Subsequently, the treatments of soil moisture content were initiated based on the irrigation program of each treatment.

**Soil moisture treatments.** For the treatments of soil moisture content, the analyses of the soil field capacity (FC) and the permanent wilting point (PWP) were undergone in the lab. FC was found at 27 % soil moisture (-0.025 MPa) while PWP was found at 13 % (-1.36 MPa). With this information, a calibration curve of soil moisture content in percentage against energy tension in megapascals (MPa) was obtained. In addition, all treatments were given general irrigation to increase the soil moisture to FC. Afterward, the soil water content was differentiated according to the specific treatment. For performing this, the irrigation times were established for each treatment. The soil moisture was allowed to be lowered to a maximum of 24 % (-0.048 MPa), 18 % (-0.23 MPa) and 14 % (-0.908 MPa), for high, medium and low soil moisture, respectively, recovering the soil moisture to 27 % (-0.025 MPa) (Figure 1) in both varieties. At the end of the study, the total applied irrigation for each treatment was counted, which were 66, 52 and 37 cm for the variety Krishna in a high, medium and low soil moisture and 62, 50 and 35 cm for the variety Rincon in a high, medium and low soil moisture, respectively.

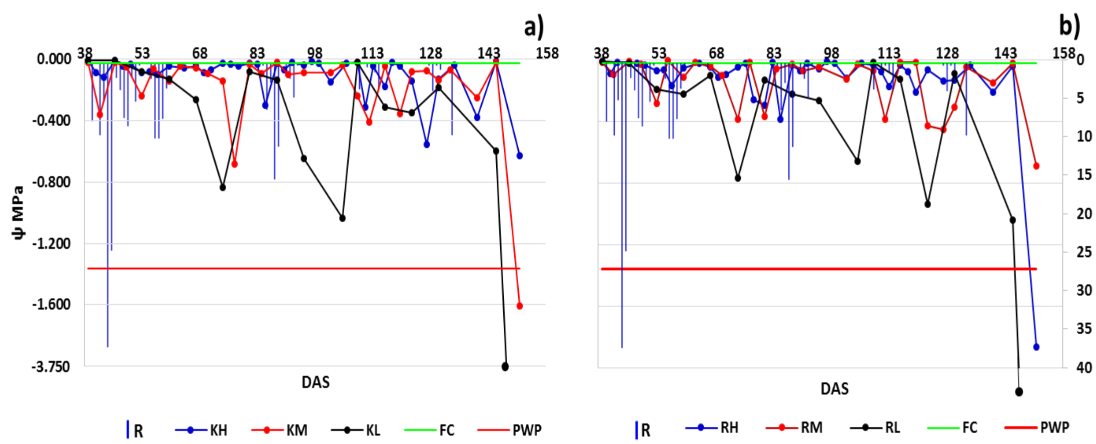



**Figure 1.** Soil moisture along the experiment with two varieties of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low) in the Comarca Lagunera México. R: rainfall; FC: field capacity; PWP: permanent wilting point.

**Measured variables.** The variables measured were plant height (PH), days to flowering of 50 % of the plants (DF), leaf area (LA), dry weight of plant (DW), source-sink relationship, harvest index (HI) and seed yield (Y). The variables of fresh and dry matter were evaluated selecting and identifying plants at random within each treatment at the end of the experiment. The seed yield variable (kg $ha^{-1}$) was evaluated by considering the seeds of the fruits of the experimental plot.

For dry weight, the parts of the plant were placed into an oven with forced air at 64 °C for 72 h or until constant weight. The leaf area was determined using a portable area meter model LI-3000C (LI-COR Biosciences, U.S.A). The harvest index (HI) was determined by equation (1):

$$HI = \frac{\mathrm{HDM}}{\mathrm{TDM}} \tag{1}$$

Where: HDM is harvestable dry matter (g); TDM is total dry matter (g).

The source-sink relationship was estimated by using equations (2) and (3):

$$SS = \mathrm{LA} * \mathrm{NAR} \tag{2}$$

$$SKS = \mathrm{DW} * \mathrm{RGR} \tag{3}$$

Where: SS = Source strength, (g d-1); LA = Leaf area; and NAR= Net assimilation rate; SKS= Sink strength (g $d^{-1}$); DW= Dry weight; RGR= Relative growth rate.

**Data analysis.** To interpret the quantitative variables, an analysis of variance was applied. In those cases in which there were significant differences between treatments, the Tukey comparison test (HSD) was used and a regression analysis adjusted to the logistic model in variables was evaluated. Statistical analysis was performed using RStudio open source software.

## RESULTS AND DISCUSSION

The data analysis for the days to flowering showed no significant differences (HSD α = 0.05) in the treatments applied. However, in both varieties, the highest soil moisture treatments produced less  days to flowering (87 DAS in both varieties) than treatments with lower soil moisture (84.5 DAS in both varieties). The range of flowering in both varieties was between 84-87 DAS (Figure 2). In other experiments, blooms are reported from 48-68 days (Anjani *et al*., 2018). Although the blooms in this experiment occurred later, seed production may not be influenced by the fast flowering, but by other characteristics such as the maturity of the raceme or the number of capsules, as reported by Rukhsar *et al.* (2018). In addition, Severino *et al*. (2012) mention that high temperatures affect the ratio of female flowers, but it would not necessarily increase seed yield.

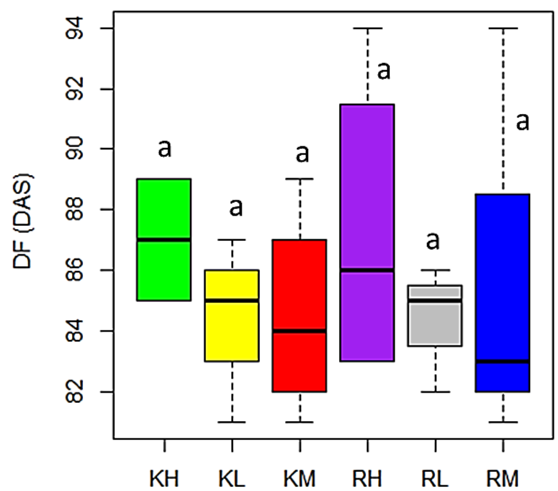
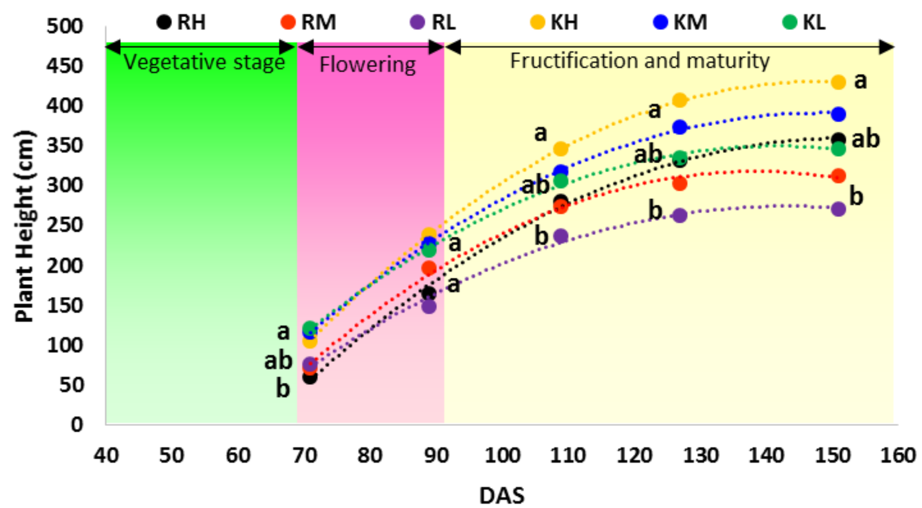



**Figure 2.** Days to flowering (DF) of two varieties of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low). Different letters indicate significant differences (HSD at α = 0.05).

Regarding plant height, significant differences (HSD α = 0.05) among the treatments were observed. In general, the Rincon variety had lower heights compared to the Krishna variety. In the same way, based on the logistic model equation used, the treatment of the Krishna variety with high soil moisture (KH) was the one that showed the highest growth rate with respect to height in the evaluated period with a maximum of 7.2 cm $d^{-1}$ at 90 DAS. On the other hand, the treatment of the Rincon variety with a low soil moisture (RL) was the one with the lowest growth rate with a final height of 270 cm. The results explain that soil moisture affects the plant height in both varieties. Therefore, at higher soil moisture greater plant height (Figure 3).

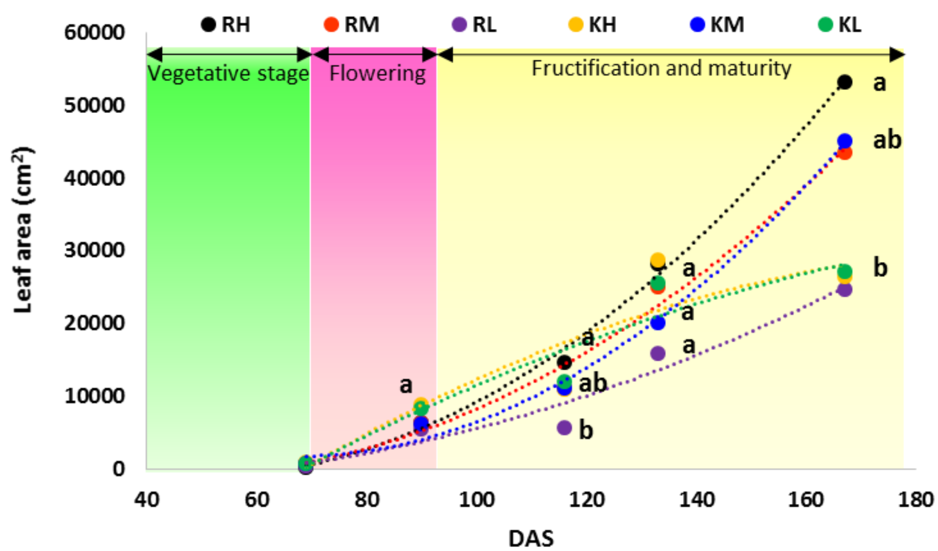
These findings contrast with those reported by Kowser (2018) and by Souza *et al*. (2018) who attained heights less than two meter in the genotypes and hybrids they used (genotypes DCH-177 and DCH-519; castor hybrids K93, respectively), so that the plant height will largely depend on the genotype or variety. The heights reported in the present study may also be due to the spacing between plants, since studies such as that of Shinde *et al*. (2018) report that lower spacing between plants favors a greater height. Furthermore, soil moisture may also favor plant height.




$$Y_{RH}=3.598E+02/(1+8.664E+02*e^{\wedge}(-7.369E-02\,X))$$
$$R^2=0.999$$
$$Y_{RM}=3.090E+02/(1+1.802E+03*e^{\wedge}(-8.97E-02\,X))$$
$$R^2=0.998$$
$$Y_{RL}=2.762E+02/(1+4.251E+02*e^{\wedge}(-7.07E-02\,X))$$
$$R^2=0.998$$
$$Y_{KH}=4.337E+02/(1+3.45E+02*e^{\wedge}(-6.7099E-02\,X))$$
$$R^2=0.999$$
$$Y_{KM}=3.97E+02/(1+1.902E+02*e^{\wedge}(-6.173E-02\,X))$$
$$R^2=0.999$$
$$Y_{KL}=3.504E+02/(1+2.269E+02*e^{\wedge}(-6.708E-02\,X))$$
$$R^2=0.999$$

**Figure 3.** Plant height of two varieties of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low) within five sampling dates (71, 89, 109, 127 and 151 days after sowing). Different letters indicate significant differences (HSD at α = 0.05).

Leaf area increased along the experiment. There were significant differences between treatments only at 116 and 167 DAS. According to the equation of the logistic model used in the leaf area, the treatment of the variety Rincon in conditions of high soil moisture was the one that presented the highest growth rate, followed by the variety Krishna in medium soil moisture. It is noteworthy that the Rincon variety ended up with a larger leaf area under high humidity conditions, but it decreased under lower soil moisture (Figure 4). From the beginning until 116 DAS, the Krishna variety presented greater growth rates for leaf area, a stage in which the flowering and fruit formation occurs. Therefore, it is very likely that this favored seed yield as it has been reported in beans (Polon-Perez *et al*., 2017).




$$Y_{RH}=6.576E+04/(1+1281.2*e^{\wedge}(-5.14E-02\,X))$$
$$R^2=0.998$$

$$Y_{RM}=5.192E+04/(1+1.48E+03*e^{\wedge}(-5.37E-02\,X))$$
$$R^2=0.995$$

$$Y_{RL}=2.962E+04/(1+8.588E+02*e^{\wedge}(-5.037E-02\,X))$$
$$R^2=0.976$$

$$Y_{KH}=2.928E+04/(1+1.822E+03*e^{\wedge}(-6.67E-02\,X))$$
$$R^2=0.932$$

$$Y_{KM}=8.435E+04/(1+5.400E+03*e^{\wedge}(-3.85E-02x))$$
$$R^2=0.998$$

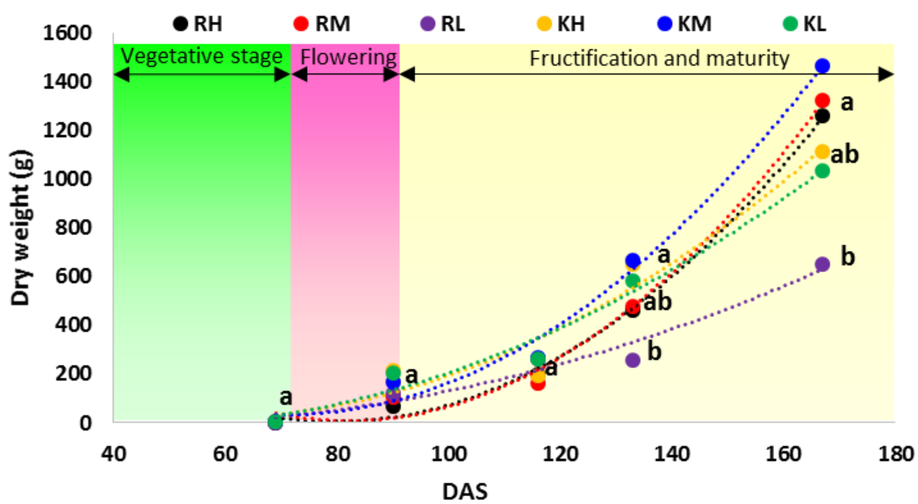
$$Y_{KL}=2.932E+04/(1+9.52E+02*e^{\wedge}(-6.03E-02x))$$
$$R^2=0.968$$

**Figure 4**. Leaf area (LA) of two varieties of castor plant (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low) within five sampling dates (69, 90, 116, 133 and 167 DAS). Different letters indicate differences (HSD at α = 0.05).

The leaf area reported in this study is larger than the results reported by Fioreze *et al*. (2018). They report leaf areas of up to 6500 $cm^2$ at 90 d and subsequently decreased while in this study, it continued to increase. These differences may be due in part to the availability of water and nutrients since plants with greater water availability tended to present greater leaf areas and growth rate. Another cause may be due to the differences between varieties, as mentioned by Ocampo *et al*. (2015).

Regarding dry weight, significant differences were found at 133 and 167 DAS favoring the treatments of the Krishna variety (HSD α=0.05). The behavior of dry weight was similar to the leaf area. The treatments of the Krishna variety with the medium soil moisture and the Rincon variety with high and medium soil moisture presented the highest dry weights at the end of the experiment (167 DAS). The

Rincon variety with low soil moisture was the one that attained the lowest dry weight (Figure 5). These differences are believed to be due to differences related to leaf area (Polon-Perez *et al*., 2017) and to a greater number of secondary stems because the stems accumulate more biomass than the leaves (Reddy and Matcha, 2010). In addition, the low increments in dry weight at the end of the experiment in the KL and RL treatments could have been because the plant focused on filling grains instead of accumulating more plant material.




$Y_{RH}$=1.779E+03/(1 + 5.636E+03*e^(-5.70E-02 X))
$R^2$=0.999

$Y_{KH}$=1.291E+03/(1 + 3.506E+03*e^(-6.028E-02 X))
$R^2$=0.978

$Y_{RM}$= -2.647E+10/(1 + (-6.245E+09)*e^(-3.444E-02 X))
$R^2$=0.995

$Y_{KM}$=1.964E+03/(1 + 2.481E+03*e^(-5.33E-02 X))
$R^2$=0.996

$Y_{RL}$=2.721E+03/(1 + 2.881E+02*e^(-2.693E-02 X))
$R^2$=0.979

$Y_{KL}$=1.379E+03/(1 + 5.806E+02*e^(-4.481E-02 X))
$R^2$=0.989

**Figure 5.** Dry weight (DW) of two varieties of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low), within five sampling dates (69, 90, 116, 133 and 167 days after sowing). Different letters indicate differences (HSD at α = 0.05).

With respect to the relationship between the source-sink strength, both varieties showed a constant demand for nutrients regardless of the soil moisture, with special attention towards the end of the sampling dates (Figure 6). The demand for nutrients in the case of the Rincon variety is believed to be more focused towards the points of vegetative growth of the plant rather than the photosynthates being transferred to the reproductive organs. The same thing seems to have happened in the case of the Krishna variety with medium soil moisture. The above, because there is a competition between sinkholes such as the flowering of the primary bunch with that of the secondary trunks in early development (Fioreze *et al*., 2016).

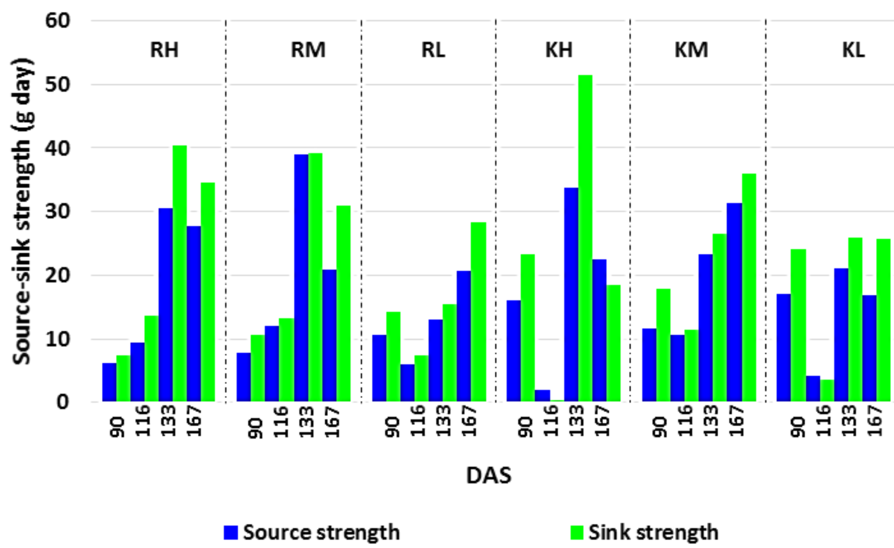



**Figure 6.** Source-Sink relationship of two varieties of castor oil plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low).

In addition, the strength of the source was higher in the KH and KL treatments at 116 DAS which could have favored the formation of reproductive organs and at the same time a photosynthetic apparatus that help the deposition of photosynthates in the formation and filling of grain in later stages. According to Severino *et al*. (2012) and Fioreze *et al*. (2018), the elimination of secondary stems promotes a high yield due to higher growth and production of the primary bunch, a shorter cycle and uniform maturity, which are considered key characteristics in the success of the crop. Therefore, it is believed that the KH and KL treatments developed few secondary stems and they focused on the nutrient demand to grain filling.

Regarding the harvest index (HI), there were significant differences in favor of the Krishna variety in low soil moisture conditions with a HI of 0.28 followed by the treatment of Krishna in high soil moisture conditions with a HI of 0.17. The treatments of the variety Rincon RH, RM and RL (0.10, 0.15 and 0.13, respectively) were the ones that reported a lower harvest index along with the medium soil moisture treatment of the Krishna variety (KM, Figure 7). This is believed to be because they developed a greater leaf area as well as a low grain yield. The harvest index of the Krishna variety with low soil moisture can be comparable to that of other grains such as corn (0.32-0.36, Kumar *et al*., 2018), so we can consider that this treatment had a good harvest index.

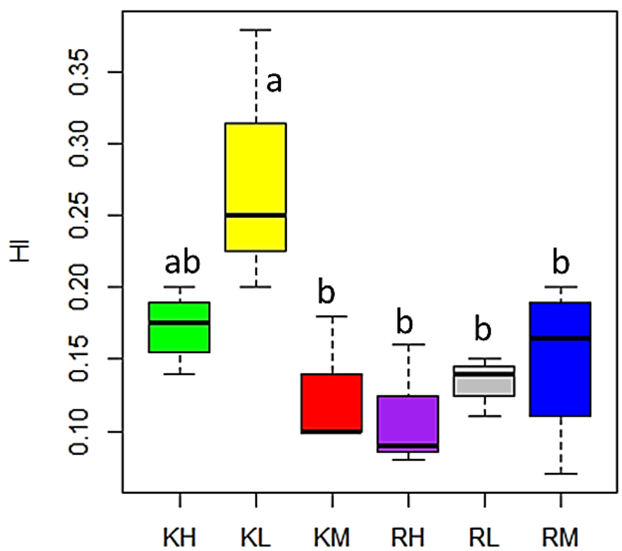



**Figure 7.** Harvest index of two varieties of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low). Different letters among bars indicate significant (HSD at α = 0.05).

In addition, Kumar *et al*. (2018a) report harvest index of 0.31 in varieties of *Ricinus communis* while Ramanjaneyulu *et al*. (2013) report averages of 0.29-0.31. This suggests that the Krishna variety has a high yield potential considering that only the crop had minimal agricultural practices. Probably, with fertilization and other agricultural practices such as those mentioned by Fioreze *et al*. (2018) can increase the yield of grain and, in turn, the harvest index.

Regarding seed yield, differences between treatments were found (HSD α = 0.05). The KL treatment was the one with the highest yield with 5220 kg $ha^{-1}$. In general, the Krishna variety presented higher yields compared to the Rincon variety, regardless of the soil moisture, although it only differed statistically with the high soil moisture treatment of this variety (RH). Also, the KL treatment did not require high amounts of soil moisture to have a good yield; the low availability of water, allowed it to deposit reserves in the seeds (Figure 8).

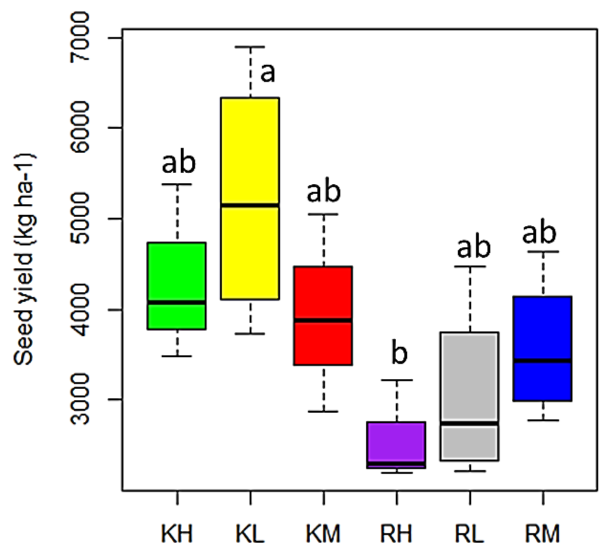



**Figure 8.** Seed yield of two varieties of castor (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low). Different letters among bars indicate significant (HSD at α = 0.05).

The yields that were obtained, mainly in the KL and KH treatments are higher than those reported by Shinde *et al*. (2018), Man *et al*. (2017) and even comparable with the fourteen genotypes studied by Shah *et al*. (2017). This is believed to be partly due to an adequate development of their photosynthetic apparatus (90-133 DAS) and also the translocation of photosynthates towards flowering, formation and filling of the fruit, instead of forming more biomass.

On the other hand, it has been observed that levels of phenotypic plasticity in the same species can vary (Ramirez, 2010), as is the osmotic adjustment in response to the water stress (Turner, 2018). Also, the osmotic adjustment is a characteristic that can be inherited and positively associated with yield (Babita *et al*., 2010; Blum, 2017). For this reason, it is also believed that the phenotypic plasticity of the plant played an important role in the evaluated varieties. The above, could have generated changes (anatomical, physiological, morphological or structural) with which it adapted in a different way to the generated environments that in our case, was at different soil moisture.

## CONCLUSIONS

Based on the results, it was found that *Ricinus communis* L. is a versatile plant that can adapt to the climatic conditions of the arid zones of Mexico. The plant shows potential as a cultivation on marginal lands with few nutrients and low water availability. In this study, the best result based on seed yield was in conditions of low soil moisture. The Krishna variety had better performance characteristics and adaptation to prolonged water deficit than the Rincon variety, a situation very common in arid areas. Among the treatments tested in this study, the Krishna variety in conditions of low soil moisture (KL) was the one that produced the best seed yields, which was favored by an adequate photosynthetic apparatus from 90 to 133 DAS period in which flowering formation and fruit filling occur. Therefore, the plant does not revealed its best reproductive performance in high soil moisture conditions.

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# CAPÍTULO IV

## Water stress and its impact on physiology and oil yield of *Ricinus communis* L in northern México

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### ABSTRACT

The castor plant (*Ricinus communis* L) is a crop with increasing economic importance in the chemical and pharmaceutical industry, and as a substitute for diesel in the production of biofuels. The objective of this survey was to evaluate the influence of the photosynthetic rate, growth and seed yield of two castor plant cultivars in a semiarid zone of Mexico. The experiment was carried out in a randomized block design with four replicates. Rincon and Krishna were the cultivars of castor plants to a population density of 13,888 plants ha$^{-1}$ using three soil moisture contents high (-0.05 MPa), medium (-0.31 MPa) and low (-0.91 MPa) in each cultivar. Photosynthetic rate ($P_N$), transpiration rate (E), stomatal conductance ($g_s$), water use efficiency (WUE), relative water content (RWC), chlorophyll content seed yield, oil yield and fatty acids content were the variables measured. Data were analyzed by variance and means tests (HSD at $\alpha$ = 0.05) and regression analysis. The highest seed yield ($P \leq 0.05$) was 5,200 kg ha$^{-1}$ with an oil yield of 2,769 L ha$^{-1}$. Krishna cultivar in low soil moisture showed the best water use efficiency and photosynthetic characteristics for cultivation in arid region of Mexico and may be an option for multiple production purposes.

**Keywords:** Hydric stress, plant physiology, oil seed, castor cultivars.

# INTRODUCTION

Castor plant *Ricinus communis* L. is a crop that has multiple uses as various parts of it can be used in agricultural, industrial, medical, and ornamental fields (Patel *et al*., 2018). Castor oil produced from castor plant seeds has long been appreciated for having an important commercial value. It has more than 700 industrial uses (Anjani, 2012). Also, it is reported as a good crop for marginal soil like the existing in semiarid areas (Severino *et al*., 2012).

The demand for castor oil has increased worldwide as a renewable energy, which has not compete with food, and is biodegradable, it has low costs and it is friendly to the environment (Shridhar *et al*., 2010). In addition, ~~it~~ the castor oil is a promising product for a variety of applications in the coming years (Patel *et al*., 2016). Castor bean has been cultivated as a substitute for diesel in the production of biofuels, mainly in arid areas of Brazil; however, little is known about the physiological mechanisms underlying their tolerance to drought (Sausen and Rosa, 2010).

In Mexico, there is interest in validating the castor plant (*Ricinus communis* L.) in commercial production (Jiménez *et al*., 2016). Despite this, in several countries there are no agronomical recommendations for its cultivation neither for the use of the plant and its residues (Domínguez *et al*., 2015). Moreover, there are still insufficient studies on the agronomic behavior and characteristics of growth and development of various genotypes, particularly in arid areas. The objective of this study was to assess the influence of soil moisture on photosynthetic rate, growth, seed yield, and oil yield of two castor cultivars in a semiarid zone of northern Mexico.

## MATERIALS AND METHODS

**Geographical location.** The experiment was conducted at the Experimental Field of Unidad Regional Universitaria de Zonas Áridas of Universidad Autónoma Chapingo, in Bermejillo Durango, Mexico. It is located at 25°53' N, 103°36' W and an elevation of 1,117 meters above sea level in a region known as Comarca Lagunera. This region has a very dry climate with summer rains, an average annual rainfall of 270 mm, with a thermal oscillation from 10 to 29 °C (CONAGUA, 2019).

**Experimental design.** The experiment was set in a randomized block design with four replicates. The seeding date was to June 30, 2016. Two cultivars of castor plants were evaluated: Rincon and Krishna. The population density was 13,888 plants $ha^{-1}$, which corresponds to seedbeds with plastic film mulch of 1.20 m wide and separation of 0.60 m between plants. The experimental unit was four seedbeds 9 m long and 1.2 m wide. The useful plot corresponded to the surface of the seven central meters from the two-central seedbeds.

**Establishment of experiment and irrigation system**. The cultivars of castor oil plants were manually seeded in the field. A tape-type drip irrigation system was used placing the lines on the soil surface with a controlled operating pressure of 16 PSI. The drip irrigation system was established from a main line pipe and side connections of PVC for each plot. The drip irrigation system was controlled by a stopcock that allowed the delivery of water according to the program of irrigation with water drawn from a deep well. After seeding and once the plants reached 15 to 20 cm in height at 39 day after sowing (DAS), an initial watering was applied to reach soil field capacity (FC). Subsequently, the treatments of soil moisture content were initiated based on the irrigation program of each treatment.

**Soil moisture treatments.** For the treatments of soil moisture content, the tests of the soil field capacity and the permanent wilting point (PWP) were undergone in the lab. FC was found at 27 % soil moisture (-0.025 MPa) while PWP was found at 13 % (-1.36 MPa). With this information, a calibration curve of soil moisture content in percentage against energy tension in megapascals (MPa) was obtained (Figure 1).

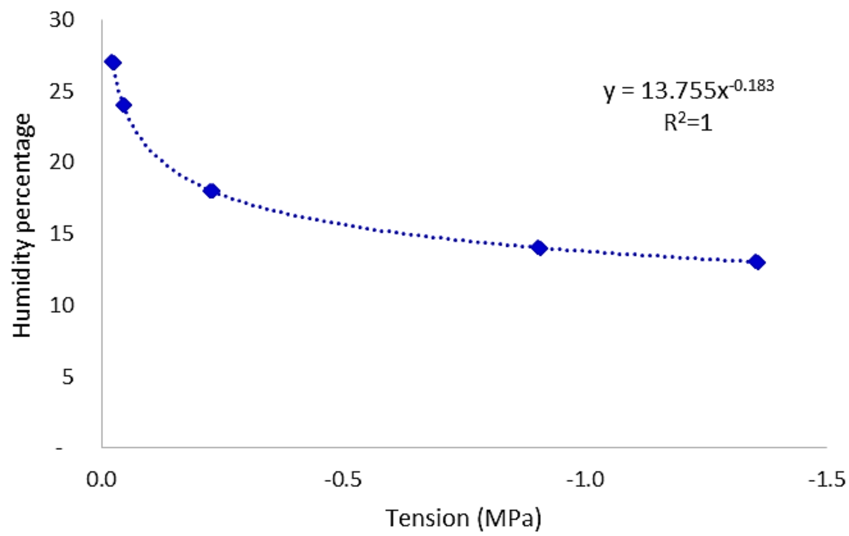



**Figure 1**. Soil moisture retention curve of the soil used in the experiment.

The irrigation times were established for each treatment according the level of soil moisture applied. The soil water content was allowed to be lowered to a maximum of 24 % (-0.048 MPa), 18 % (-0.23 MPa) and 14 % (-0.908 MPa) for high, medium and low soil moisture, respectively, followed by an irrigation to recover FC (Figure 2) in both cultivars. The soil moisture content was periodically measured at 30 cm depth by the gravimetric method. At the end of the study, the total applied irrigation was counted, which were in average of 64, 51 and 36 cm for the treatments with high, medium and low soil moisture, respectively.

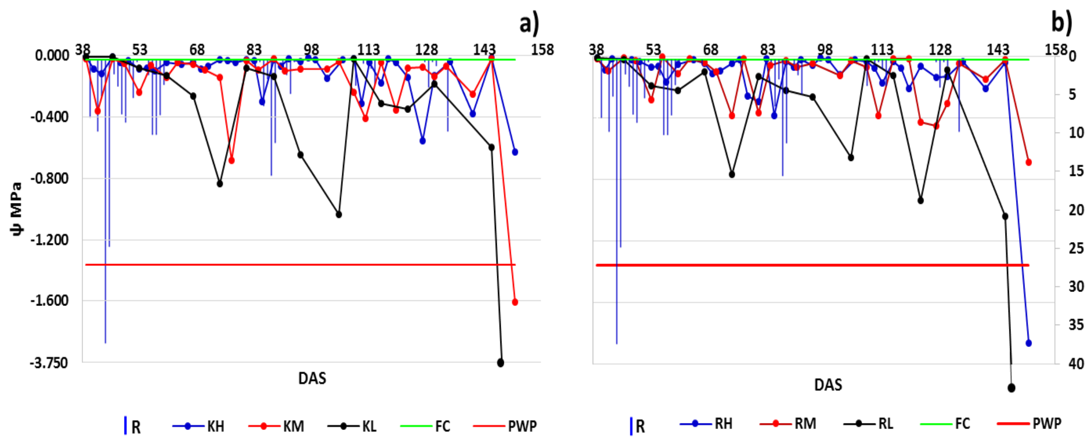



**Figure 2.** Soil moisture along the experiment with two cultivars of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = High, M = Medium, L = Low) in the Comarca Lagunera México. R: Rainfall; FC: Field capacity; PWP: Permanent wilting point.

**Oil extraction**. The extraction of oil was carried out by means of the immersion-percolation method with Soxhlet using ethanol 96 % as solvent. The castor bean seeds were dried at 70 °C in an oven for 24 h. After that, 5 g of the sample previously crushed were taken and placed in the Soxhlet equipment for 6 hours. After 6 h in reflux of the sample, the solvent was emptied into a previously weighed container and the ethanol was evaporated through a heating oven at 75 °C to obtain a constant weight. The oil yield was obtained by differences in the weight of the container with the following equation:

$$Oil\ yield\ (\%) = \frac{wt\ 2 - wt\ 1}{sample\ wt} * 100$$

Where: wt 1 = empty flask weight (initial weight), wt 2 = flask weight with oil (final weight), sample wt = sample weight of seeds.

**Analysis of the oil**: The fatty acids profile was made by gas chromatography. The sample was saponified with sodium methoxide and esterified with boron trifluoride. It was carried out in an Agilent 6820 gas chromatograph, with flame ionization detector (FID) and the Cerety software for the analysis of retention times and areas. A melted silica capillary column with D-Wax Agilen® polar phase, 60 m long, 0.25 mm internal diameter and 25 μm stationary phase was used. The identification was carried out by means of a standard mixture of fatty acids methyl esters (FAME) (Supelco No. 47885-U). The acid value, peroxide value and the saponification value were determined by the methods indicated in Mexican standards NMX-F-101-1987, NMX-F-154-1987 and NMX-F-174-S-1981, respectively, using the following equations:

$$AV = \frac{56.1\ x\ N\ x\ V}{P}$$

Where: AV = Acid value, 56.1 = chemical equivalent of potash, N = normality of potassium hydroxide solution, V = $cm^3$ of standard solution of potassium hydroxide spent in the titration of the sample, P = mass of the sample in grams.

$$PV = \frac{(A - A1)x\ N\ x\ 1000}{M}$$

Where: PV = Peroxide value, A = Milliliters of sodium thiosulfate solution spent in the titration of the sample, A1 = ml of sodium thiosulfate solution spent in the titration of the blank, N = Normality of the thiosulfate solution of sodium, M = Mass of the sample in grams.

$$SV = \frac{(V1 - V)x\ 28.05}{P}$$

Where: SV = Saponification value, V1 = Cubic centimeters of hydrochloric acid solution at 0.5 N used in the titration of the control, V = Cubic centimeters of hydrochloric acid at 0.5 N used in the titration of the sample, P = Mass of the sample in grams, 28.05 = Milligrams of potassium hydroxide equivalent to 1 $cm^3$ of hydrochloric acid at 0.5 N.

**Physiological variables.** The photosynthetic rate ($P_N$), transpiration rate (E) and stomatal conductance ($g_s$) were measured with a portable photosynthesis meter LI-6400XT (LI-COR Biosciences, U.S.A). Water use efficiency (WUE) was calculated with the values of $P_N$, and E (WUE = $P_N$/E). Relative water content (RWC) of leaves was estimated using the method described by Smart and Bingham (1974). The chlorophyll content was determined using a SPAD chlorophyll meter (Fieldscout CM 1000) and were considered nine readings for each experimental unit. The seed yield variable (kg $ha^{-1}$) was evaluated by considering the seeds of the fruits of the useful plot.

Water productivity is the quotient between the production and the volume of irrigation water applied expressed in productive terms (kg $m^{-3}$), using the following equation:

$$WP = \frac{Y}{I}$$

Where: WP = Productivity of applied water, Y = Yield of seed or oil in kg, I = Water applied by irrigation in $m^3$.

**Data analysis.** To interpret the quantitative variables, an analysis of variance was applied, in those cases in which there were significant differences among treatments, the Tukey comparison test (HSD) was done and also a correlation and regression analysis. Statistical analysis was performed using RStudio open source and Minitab software version 17.1.

## RESULTS AND DISCUSSION

According to the data analysis for relative water content, there were significant differences among treatments at 81, 109 and 144 DAS (HSD $\alpha = 0.05$). The RWC was more stable in high soil moisture in both castor cultivars (Figure 3a, 3b), and when the soil moisture decreased, the variation on RWC increased (Figure 3c, 3d, 3e, 3f). This means that there is an effect of soil water potential on the water status of the plant. In the case of the Rincon cultivar, when it was subjected to lower water potentials, the RWC decreased (Figure 3b, d, f). However, this behavior was not presented in Krishna cultivar. It should be noted that the KL treatment despite being subjected to tensions close to PWP, maintained RWC values equal or better than the high soil moisture treatments from 95-144 DAS (Figure 3e). The above may be due to a response of the plant to close the stomata when the soil's water potential decreases. In species of the Euphorbiaceae family, it has been found a relationship between soil water potential and stomata closure as a strategy of tolerance to a water deficit (Hsie *et al*., 2015, dos Santos *et al*., 2013), and in this way maintain the water status of the plant.

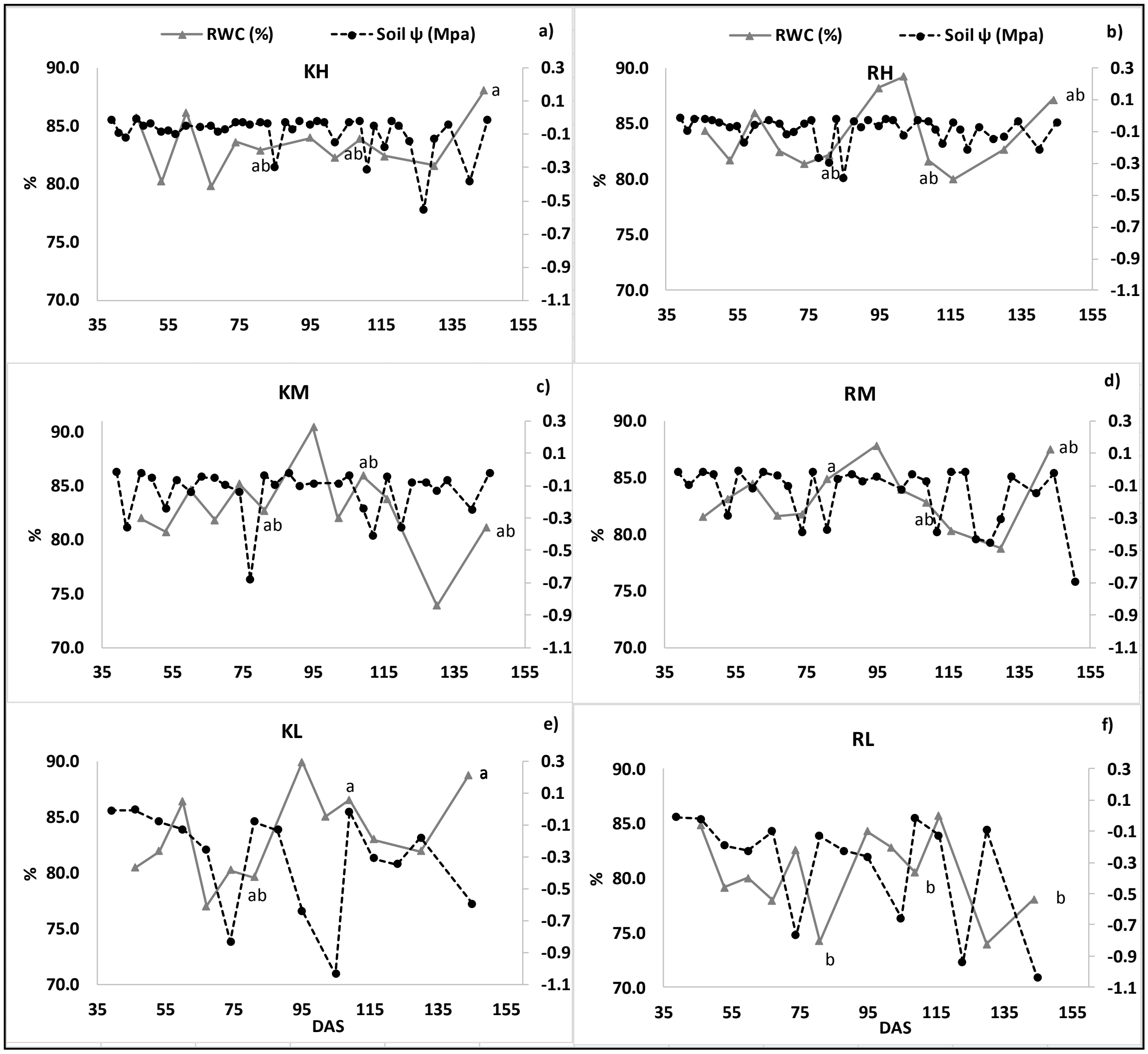



**Figure 3.** Relative water content (RWC) and water potential of soil of two cultivars of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = high, M = medium, L = low), in the Comarca Lagunera, Mexico. Different letters among treatments in RWC indicate significant differences (HSD at α = 0.05).

Water use efficiency was increased when water potential of the soil decreased. Both castor cultivars evaluated in this study were more efficient in the use of water in conditions of medium and low soil moisture (Figure 4). The Krishna cultivar had 22 % and 16 % greater efficiency towards the end of the period evaluated in medium and low humidity conditions, respectively as compared with the results under high humidity (Figure 4a, 4c, 4e). The Rincon cultivar registered water use efficiencies in medium and low soil moisture conditions were 11 % and 6 %

greater than that measured under high humidity. Also, the highest WUE was registered for all the treatments in the same period (103–115 DAS), which correspond to the phenological stage of fructification.

The water use efficiency could be related to the osmotic adjustment capacity of the plant. It has been observed that plants with better adjustment capacity are more efficient in the use of water and have a greater tolerance to drought (Berry *et al*. 2010). In addition, the plants with lower WUE have a greater accumulation of biomass as the effect of high photosynthesis, but also with major transpiration, which cause a water deficit in critical stages such as grain filling (Wang et al., 2011).

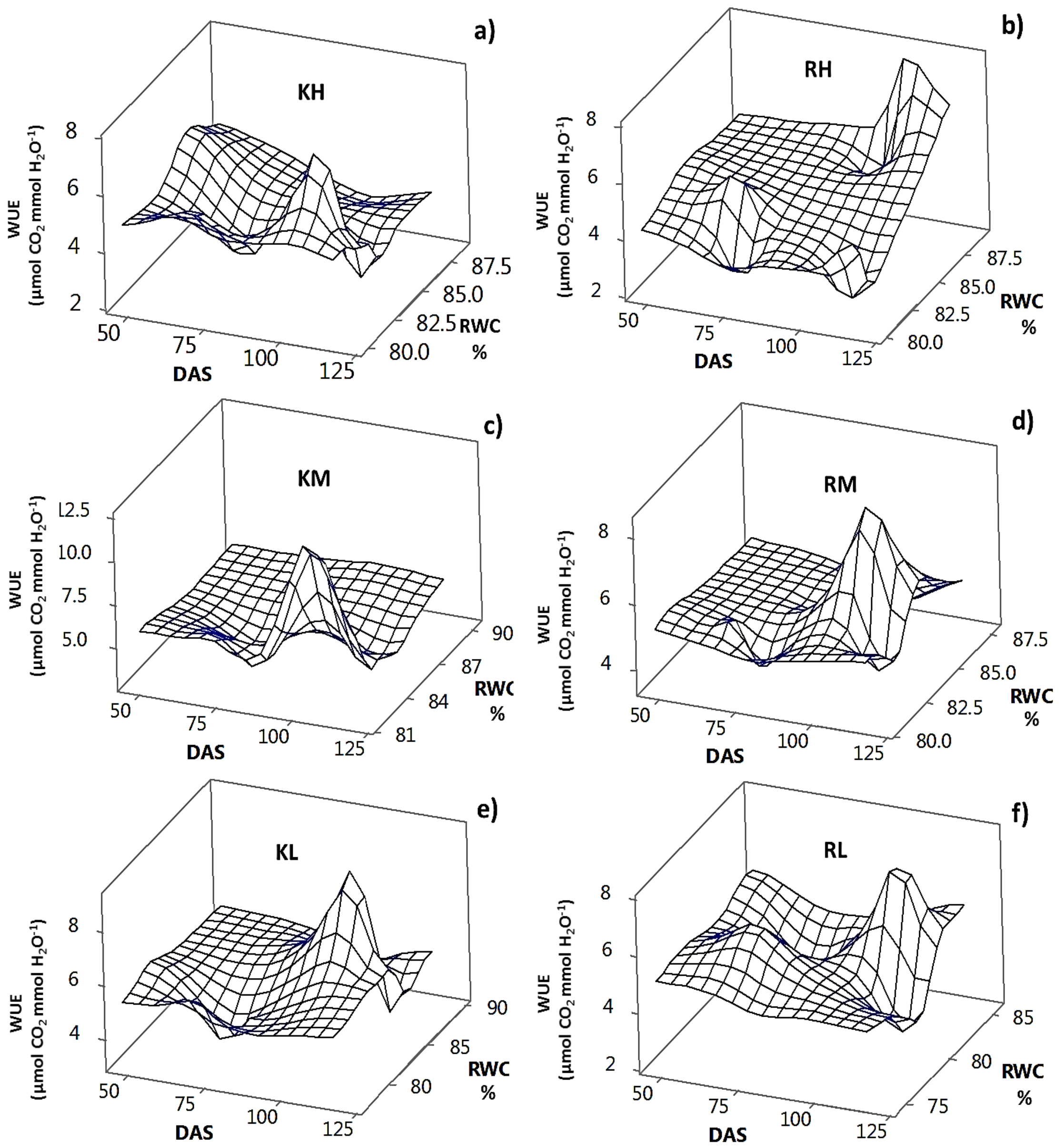



**Figure 4**. Water use efficiency (WUE) and relative water content (RWC) of two cultivars of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = high, M = medium, L = low), in the Comarca Lagunera, Mexico.

Regarding the stomatal conductance, the Rincon cultivar showed higher $g_s$ (16 %) than the Krishna cultivar, indicating that there is greater opening of the stomata and therefore greater gas exchange. For its part, the Krishna cultivar showed lower values of $g_s$, mainly when it was evaluated to a medium moisture content in the soil. In this condition, $g_s$ was 18 % and 6 % lower than in high and low soil moisture content, respectively. In both cultivars the $g_s$ values decreased as a function of time. These differences may account for a greater WUE in Krishna, since a lower stomatal conductance may reduce transpiration more than photosynthesis. According to several authors, photosynthesis is directly related to stomatal conductance (McAdam and Brodribb, 2012; Lauteri *et al*., 2014). In this study, a similar behavior was observed from the beginning until 90 DAS. However, after 90 DAS the photosynthesis rate in some cases increased even though the stomatal conductance decreased (Figure 5a, 5b, 5c, 5d, 5f).

The photosynthesis rate showed significant differences at 96, 103, 110 and 123 DAS (HSD $\alpha = 0.05$). In general, the Rincon cultivar showed higher $P_N$ in the treatment of low and medium soil moisture with averages of 29.7 and 29.22 μmol $CO_2$ $m^{-2}$ $s^{-1}$, respectively. These same treatments had their maximum peak at 103 DAS (50.4 and 42.5 μmol $CO_2$ $m^{-2}$ $s^{-1}$, Figure 5c, 5e). It is to be noted that the treatments of high soil moisture showed lower general averages of $P_N$ (25.45 μmol $CO_2$ $m^{-2}$ $s^{-1}$ in both treatments) as compared to the treatments of low soil moisture (29.7 μmol $CO_2$ $m^{-2}$ $s^{-1}$ in RL and 26.15 μmol $CO_2$ $m^{-2}$ $s^{-1}$ in KL).

The increase in photosynthesis despite a decrease in $g_s$ may be due to an effective stomatal control mechanism to regulate $g_s$ and prevent excessive water loss and continue the photosynthesis under progressively drier conditions (Johnson *et al*., 2018). Furthermore, not all plant species, or individuals within a species, possess equally effective stomatal control, as the speed and "tightness" of the closure (Haworth *et al*., 2011.), a situation that could have happened in the cultivars evaluated in this study. Therefore, castor bean crop in conditions close to PWP maintains the photosynthetic rate and increases the WUE. This could mean a considerable water saving (28 cm = 2800 $m^3$ per hectare in average) without compromising photosynthesis and yield.

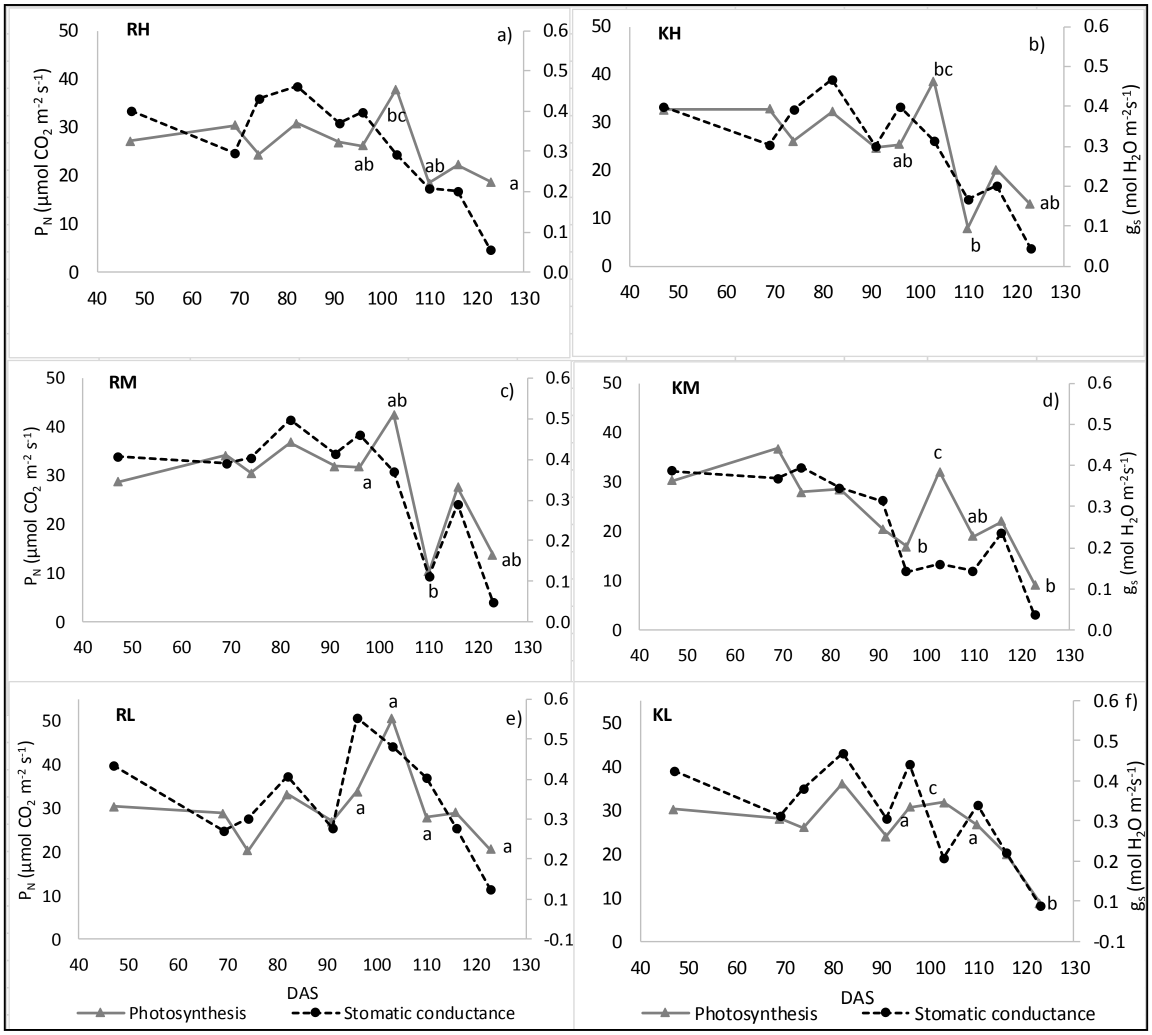



**Figure 5.** Photosynthesis rate ($P_N$) and stomatal conductance ($g_s$) of two cultivars of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = high, M = medium, L = low), in the Comarca Lagunera, Mexico. Different letters among treatments in photosynthesis indicate significant differences (HSD at α = 0.05).

Regarding transpiration, there were significant differences among treatments at 96, 103, 110 and 123 DAS (HSD α = 0.05, Figure 6). Rincon cultivar showed up to 16 % more E as compared to that of Krishna cultivar. This may explain the lower WUE of Rincon cultivar. In the case of the Krishna cultivar under high soil moisture, E was higher (Figure 6a) and, when the humidity in the soil was lower, E decreased by 15 % and 10 % in the treatments of medium humidity (KM) and low humidity (KL), respectively (Figure 6c, 6e).

Also, Rincon cultivar in the treatment of medium soil moisture was the one that presented the higher E, 8 % more with respect to the high soil moisture treatment (RH, Figure 6d). The treatment of low soil moisture (RL) had 2.5 % less transpiration than the treatment of high soil moisture (Figure 6f). For the above, it can be observed that the stomatal conductance affected the transpiration. When the plant presented higher stomatal conductance, also the plant presented higher transpiration. It has been reported in several studies that there is a strong correlation between E and $g_s$ both in field conditions (Santos *et al*., 2017) as well as in greenhouses (de Freitas *et al*., 2011), and even under saline stress (Neto *et al*., 2014; Sun *et al*., 2013).

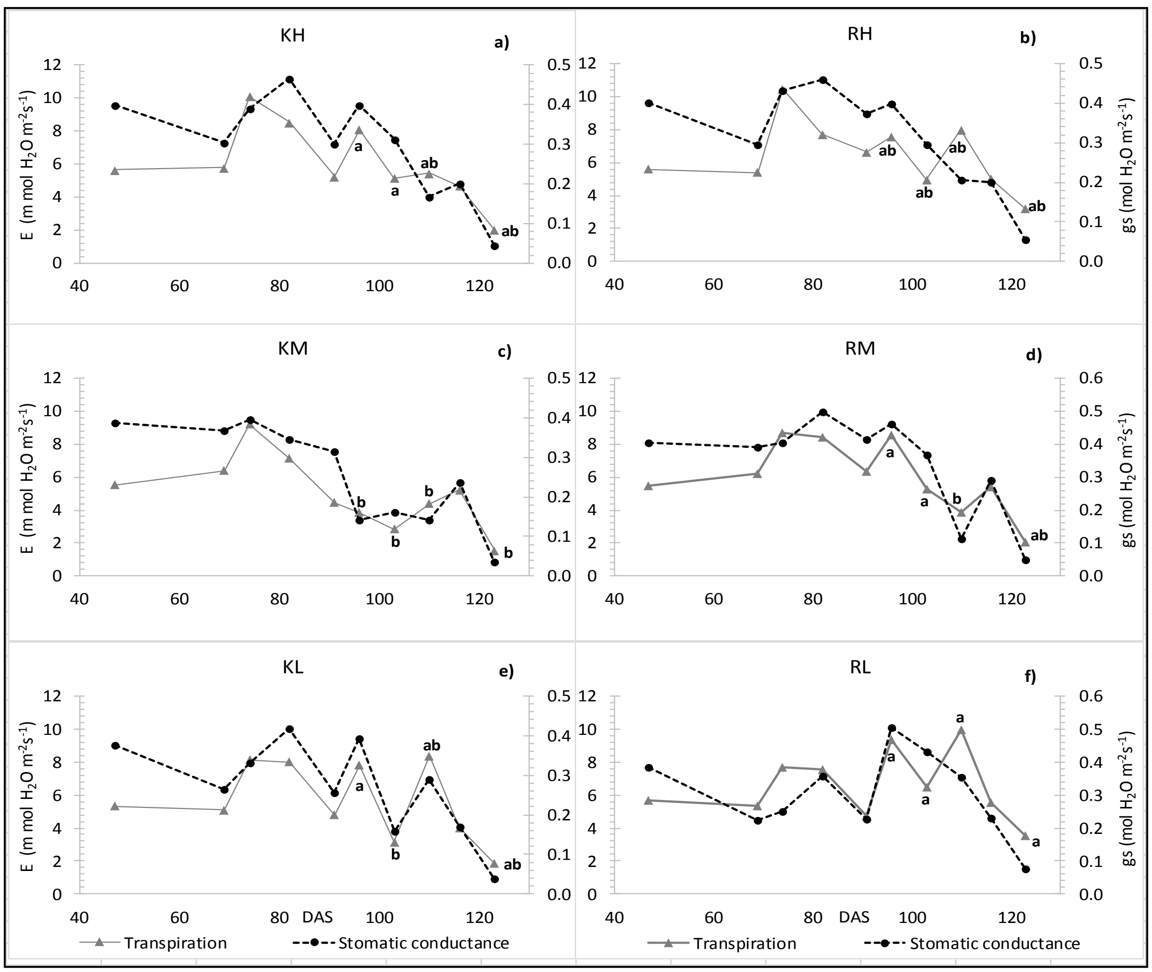
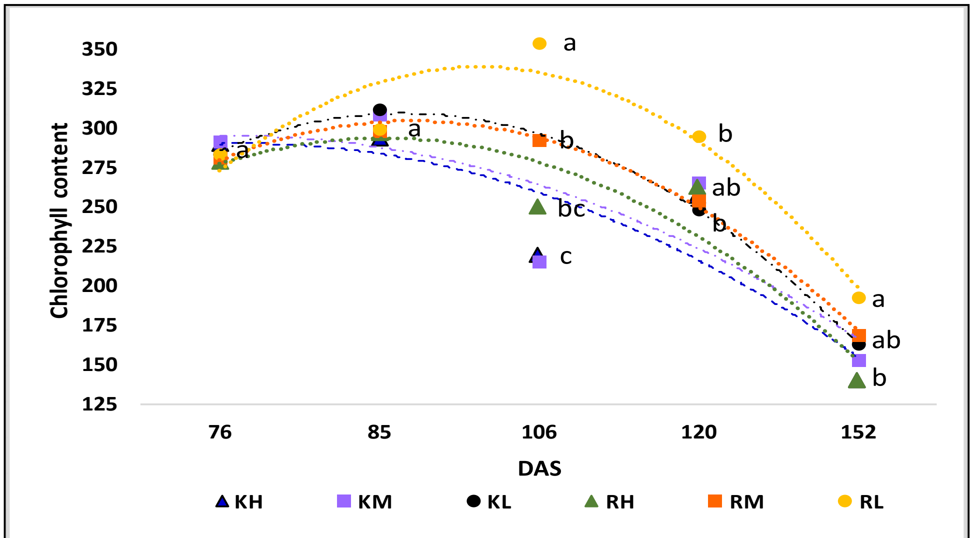



**Figure 6.** Transpiration (E) and stomatal conductance ($g_s$) of two cultivars of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = high, M = medium, L = low), in the Comarca Lagunera, Mexico. Different letters among treatments in transpiration indicate significant differences (HSD at α = 0.05).

The chlorophyll content showed significant differences from the 106 DAS, with a behavior very similar to that of photosynthesis. The treatment of the Rincon cultivar in low soil moisture (RL) showed the highest chlorophyll content followed by the Krishna cultivar in low soil moisture (KL) and Rincon in medium humidity (RM). The treatments that showed the lowest chlorophyll content were the treatments in high soil moisture conditions (Figure 7). The above agrees with the results or Salazar *et al*. (2014), who find a greater amount of chlorophyll pigments in plants of banano cv. 'Pineo gigante' (Musa AAA) under water stress. In addition, Borjas-Ventura *et al*. (2019) reported increases in photosynthetic pigments in *Panicum maximum* Jacq plants under warming and water deficit. This seems to indicate that the production of energy capturing pigments is favored, above the pigments responsible for photo-protection, perhaps as a maintenance strategy of photosynthesis under conditions of limited water and gas exchange (Salazar *et al*., 2014). In addition, several studies indicate that abundance of photosynthetic pigments may be related to the high hydric stress tolerance that permits to maintain the chlorophyll content by keeping the water in the tissues (Rizwan *et al*., 2018, de Silva *et al*., 2012). The increase in pigments and higher photosynthesis may be responsible for the production of biomass in the case of the Rincon cultivar, and the production of seed in the Krishna cultivar.




| | |
|---|---|
| RH y=6.10E-02/(1 + (-0.99)*e^(-1.68E-06x)) $R^2 = 0.8343$ | KH y=2.79E-02/(1 + (-0.99)*e^(-9.10E-07x)) $R^2 = 0.8755$ |
| RM y=5.55E-02/(1 + (-0.99)*e^(-1.172E-06x)) $R^2 = 0.8253$ | KM y=6.57E-02/(1 + (-0.99)*e^(-1.97E-06x)) $R^2 = 0.8508$ |
| RL y=7.85E-02/(1 + (-0.99)*e^(-9.59E-07x)) $R^2 = 0.5574$ | KL y=-5.19E-02/(1 + (-1E+00)*e^(-(-1.23E-06)x)) $R^2 = 0.9684$ |

**Figure 7**. Chlorophyll content of two cultivars of castor plants (K = Krishna, R = Rincon) and three levels of soil moisture (H = high, M = medium, L = low), in the Comarca Lagunera, Mexico, within five sampling dates (76, 85, 106, 120 and 152 days after sowing). Different letters indicate significant differences (HSD at α = 0.05).

Regarding seed yield, differences among treatments were found (HSD α = 0.05). The KL treatment was the one with the highest yield with 5220 kg $ha^{-1}$. In general, the Krishna cultivar presented higher yields compared to the Rincon cultivar, regardless of soil moisture. Although it only differed statistically with the high soil moisture treatment of this cultivar (RH, Table 1). Concerning the percentage of oil in the seed, significant differences can be observed among treatments (HSD α = 0.05). In general, the Rincon cultivar showed higher percentages of oil in the seed. However, there were not statistically different from the oil yield of the Krishna cultivar under low soil moisture (Table 1).

On the other hand, there are significant differences in oil yield per hectare (HSD α = 0.05). The treatment with the highest oil yield was that of the Krishna cultivar in low soil moisture conditions it yielded approximately 67 % more oil per hectare than the best treatment of Rincon cultivar. This was as a result of the combination of high seed yield and relatively high percentage of oil in the seeds (Table 1).

Water productivity is an important agronomic indicator in areas with limited water resources which allows to analyze how the economic value of irrigation water can be maximized (Gallardo *et al*., 2007). This parameter may vary depending on the regions and the type of crop; however, it is a good measure as a strategy to evaluate crop productivity and consider the different uses the water (Seckler *et al*., 2003). In this way, the water productivity in this study showed significant differences (HSD α = 0.05) in favor of the KL treatment with an average of 1.41 kg of seed per $m^3$ of water and 0.66 kg of oil per $m^3$ of water. Water productivity for seed and oil yield in Krishna cultivar under low soil moisture almost duplicated that found in the other treatments. It is noteworthy that the high moisture treatments presented the lowest water productivity in both seed and oil (Table 1). According of that, this is important in arid zones to optimize the efficiency of water, which is used in agriculture.

**Table 1.** Oil yield, percentage of oil in seeds and water productivity of two cultivars of castor plants and three levels of soil moisture in the Comarca Lagunera México.

| CULTIVAR | Soil moisture level | Seed yield (kg $ha^{-1}$) | Oil yield (L $ha^{-1}$) | Oil in seed (%) | Water productivity (kg seed $m^{-3}$) | Water productivity (kg oil $m^{-3}$) |
|---|---|---|---|---|---|---|
| **Krishna** | High | 4252 ab | 1619 b | 40.9 b | 0.64 b | 0.26 b |
| | Medium | 3936 ab | 1639 b | 41.5 b | 0.75 b | 0.31 b |
| | Low | 5228 a | 2769 a | 46.3 a | 1.41 a | 0.66 a |
| **Rincon** | High | 2570 b | 1245 b | 47.5 a | 0.41 b | 0.20 b |
| | Medium | 3569 ab | 1662 b | 46.3 a | 0.71 b | 0.33 b |
| | Low | 3040 ab | 1242 b | 47.9 a | 0.87 b | 0.41 ab |

Different letters among columns indicate significant differences (HSD at α = 0.05).

The seed yields found in this study mainly in the KL treatment were higher than those reported by Shinde *et al*. (2018), Man *et al*. (2017) and even competitive with those genotypes studied by Shah *et al*. (2017). Moreover, the averages found in oil yield percentage are lower than those reported by Danlami *et al*. (2015) who registered averages of 58.8% using ethanol as solvent. The yields found in this study were related to the WUE, since the treatments with better yields showed a better water use efficiency, combined with high values of $P_N$ at critical stages such as the flowering stage and fructification which translated into good yields. Also, the KL treatment showed greater water efficiency especially in the fructification stage despite having a lower stomatal conductance at the end of the experiment. Therefore, it is believed that the plants were more efficient in depositing photo-assimilates towards the development of the seed and not towards the formation of biomass. In addition, the constant variation in stomatal conductance allowed adjustments to be made that allowed photosynthesize and reduced water loss (Wang *et al*., 2011). On the other hand, the osmotic adjustment is a characteristic that can be inherited and positively associated with yield (Babita *et al*., 2010; Blum, 2017). For this reason, it is also believed that the osmotic adjustment played an important role in the evaluated cultivars which allowed the plant to adapt a different way to the generated environments.

Regarding oil quality, differences were found among treatments (HSD $\alpha = 0.05$). In those referring to the acid value (AV), low values are observed especially in the treatments of low soil moisture (0.43, 0.45 mg KOH $g^{-1}$ in KL and RL treatment, respectively, Table 2), which expressed in percentage of oleic acid corresponds to values of 0.22 % and 0.23 %. The acid values are within the international standard for fats and virgin oils, whose limit value is 4.0 mg KOH $g^{-1}$ (Alimentarius, 2015) and are even lower to the refined castor oil reported by Muhammad *et al*. (2019) which obtained 2.8 mg KOH $g^{-1}$ sample.

Regarding the peroxide value (PV), low values were found which indicates that castor oil is stable during extraction and storage. According to international standards for fats and oils, the peroxide value should be up to 15 milliequivalents of active oxygen $kg^{-1}$ of oil (Alimentarius, 2015). For the saponification value (SP), significant differences were found (HSD $\alpha = 0.05$); the KL treatment is the one with the lowest value and very similar to that reported by Danlami *et al*. (2015) with an average of 174 mg of KOH $g^{-1}$. The fatty acid profile shows that the oil is mainly composed of ricinoleic acid (77-82 %, Table 2).

The differences in the quality parameters evaluated are likely to be due to differences in the cultivars, and to the different conditions to which they were subjected. It has been reported that oil content and physicochemical characteristics are affected by genotype and environmental conditions (Omohu *et al*. (2017). In addition, the oil quality parameters found in this study are within the ranges found by other authors such as Bekele *et al*. (2018), Omohu *et al*. (2017), Shah *et al*. (2017) and Danlami *et al.* (2015). On the other hand, castor oil is unique due to its high content of ricinoleic acid and the hydroxyl functionality of ricinoleic acid which provides good stability to oxidation, shelf life and a reaction point for several chemical reactions (Mobofu, 2016). For this reason, it is a promising product for a variety of applications in the coming years, such as polyurethane foam based on castor oil (Trovati *et al*., 2019) or even in the energy industry as a source of renewable energy (Patel *et al*. , 2016).

**Table 2.** Oil quality and fatty acids profile of two cultivars of castor plants and three levels of soil moisture in the Comarca Lagunera México.

| CULTIVAR | Soil moisture level | AV (mg KOH $g^{-1}$) | PV (meq $O_2$ $kg^{-1}$) | SV (mg KOH $g^{-1}$) | Fatty acid profile | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Palmitic (C 16:0) % | Stearic (C 18:0) % | Oleic (C 18:1) % | Linoleic (C 18:2) % | Ricinoleic (C18:1) % |
| Krishna | High | 0.63 b | 1.78 c | 173.9 b | 1.84 | 1.74 | 4.19 | 8.21 | 81.59 |
| | Medium | 0.46 a | 1.25 b | 181.2 a | 1.8 | 1.64 | 3.95 | 7.78 | 82.58 |
| | Low | 0.43 a | 0.47 a | 172.6 b | 2.33 | 2.02 | 4.68 | 10.3 | 77.58 |
| Rincon | High | 0.57 b | 0.99 b | 176 ab | 2.09 | 1.94 | 4.66 | 8.47 | 80.37 |
| | Medium | 0.89 c | 0.99 b | 175.5 ab | 2.25 | 1.76 | 3.56 | 9.66 | 80.98 |
| | Low | 0.45 a | 1.86 c | 176.8 ab | 2.13 | 1.64 | 4.32 | 7.22 | 82.58 |

Different letters among columns indicate significant differences (HSD at $\alpha = 0.05$).

## CONCLUSIONS

The Krishna cultivar was more efficiency to keep a higher photosynthesis and less transpiration, which produced a greater water use efficiency and production of photoassimilates than the Rincon cultivar. The Rincon cultivar had higher percentages of oil in the seed; however, the Krishna cultivar has higher seed yields and therefore better oil yields per hectare than the Rincon cultivar. Krishna cultivar under low soil moisture conditions (KL) had the best physiological answers, and also it had the higher water productivity with 1.41 kg of seed $m^{-3}$, and 0.66 kg of oil $m^{-3}$, which could mean a saving of water of up to 2,900 $m^3$ per hectare without affecting the crop productivity. Therefore, Krishna cultivar can be used to produce oil under arid zones conditions.

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