

Selection of genotypes of the biofuel crop *Jatropha curcas* collected in Mexico using a multivariate approach

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Abstract

Jatropha curcas L. has attracted much interest towards its establishment as an extensive crop, due to the high amount and quality of oil from its seeds, which can be transformed into biofuels. However, a limitation is the lack of varieties with outstanding agronomic performance. Therefore, the aim of this study was to select candidate genotypes of *J. curcas* collected in Mexico and grown under common garden conditions, using a multivariate approach. Twenty-nine genotypes were studied during the cycle of February 2014 to January 2015, evaluating 12 quantitative and six qualitative traits. The data were processed by multivariate analysis, and the technique of paired comparisons was utilized for the selection of genotypes. Fruit production was presented from February to November, with the accession MAP-8 being the most productive. The most important variables, identified by Principal Component Analysis, were productive cycle, dehiscence, number of inflorescences, number of ripe fruits, pulp fresh weight, number of seeds, seed weight, seed dry weight, plant height, diameter of stem, and oil potential yield. The outstanding genotypes were ARR-7 with 88 points, CDCU-1 with 85 points, MAP-8 with 84 points and PIN-1 with 81 points. The results of this study contribute to the selection of candidate genotypes for planting in the field but will require further evaluation in the context of environmentally friendly practices.

Keywords:

Agronomic traits
Biodiesel
Bioenergy crops
Candidate genotypes

Palabras clave:

Rasgos agronómicos
Biodiesel
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Genotipos candidatos

Selección de genotipos élite de *Jatropha curcas* recolectados en México mediante análisis multivariado de rasgos agronómicos

Resumen

Jatropha curcas L. ha despertado interés para su establecimiento como cultivo extensivo, debido a la elevada cantidad y a la calidad del aceite de sus semillas, el cual puede transformarse en biocombustibles. Sin embargo, una limitación es la falta de variedades con un desempeño agronómico sobresaliente. Por ello, el objetivo de este estudio fue seleccionar genotipos candidatos de *J. curcas* recolectados en México y cultivados en condiciones de jardín común, empleando un enfoque multivariado. Se estudiaron 29 genotipos durante el ciclo de febrero de 2014 a enero de 2015, evaluando 12 caracteres cuantitativos y seis cualitativos. Los datos se procesaron mediante análisis multivariado y se utilizó la técnica de comparaciones pareadas para la selección de los genotipos. La producción de frutos se registró de febrero a noviembre, siendo la accesión MAP-8 la más productiva. Las variables más importantes, identificadas mediante Análisis de Componentes Principales, fueron: ciclo productivo, dehiscencia, número de inflorescencias, número de frutos maduros, peso fresco de la pulpa, número de semillas, peso de la semilla, peso seco de la semilla, altura de la planta, diámetro del tallo y rendimiento potencial de aceite. Los genotipos sobresalientes fueron ARR-7 con 88 puntos, CDCU-1 con 85 puntos, MAP-8 con 84 puntos y PIN-1 con 81 puntos. Los resultados de este estudio contribuyen a la selección de genotipos candidatos para su plantación en campo, aunque requerirán evaluaciones adicionales en el contexto de prácticas respetuosas con el medio ambiente.

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1. Introduction

Jatropha curcas L. is an oilseed plant that is water stress tolerant and adaptable to poor soils (Divakara et al., 2010). Conventionally it has been used as a living fence (Abdelwanis et al., 2025) and in traditional medicine (Martínez-Herrera et al., 2006), although in the last decade its extensive cultivation has been implemented, because the oil from its seeds is of good quality for the production of biofuels (Alhammad et al., 2023). One limitation to developing it into crops is the lack of indexed varieties with outstanding agronomic performance.

Only a few lines of high-performance genotypes of *J. curcas*, as SDAUJ® derived from genotypes of India (Basha and Sujatha, 2007; Surwenshi et al., 2011) and Jmax-100® derived from germplasm from Guatemala (Eswaran and Johnson, 2012) have been developed. Although there are an increasing number of seed trading companies that offer elite varieties of *J. curcas* (Wang et al., 2026), the methods that these companies use to select varieties have not been published. A new crop as *J. curcas* requires the selection of genotypes with outstanding agronomic performance, their evaluation and field validation, and the multiplication of genetic resources, particularly those native to the center of origin and diversity of this species: the Mesoamerican region (Neupane et al., 2021; Ovando-Medina et al., 2009; Ovando-Medina et al., 2011a).

Some research has attempted to delineate strategies for selecting *J. curcas* genotypes, as performed by Kaushik et al. (2007), who employed the traits of the seeds and the oil content as indicators of agronomic quality. Meanwhile, Sunil et al. (2008) preferred using phenotypic traits of plants as a method of identifying superior lines by evaluating: plant height, collar diameter, number of primary branches, petiole length, number of fruits per cluster, pedicel length, and yield. Mishra (2009), using paired comparisons of morphological and productive traits, found that with the percentage of oil and seed yield he could select the most promising accessions.

The above studies have used germplasm collected in the Old World, particularly India, while Mesoamerican germplasm remains little explored. In this respect it may be mentioned that there has been some research on the traits of *J. curcas* plants collected in Mexico (Martínez-Herrera et al., 2006); however, the phenotype is caused by the interaction of the genotype with the environment; therefore, an evaluation of the traits is required under homogeneous environmental conditions. Consequently, the aim of this study was to evaluate the agronomic performance of accessions of *J. curcas* collected in Mexico grown under common garden conditions.

2. Materials and Methods

2.1. Study area

The study was conducted at the *Jatropha* Germplasm Bank of the Instituto de Biociencias (IBC), Universidad Autónoma de Chiapas (Mexico). Site data (14.4976 North, 92.4774 West) are: altitude of 58 meters above sea level, average temperature of 30.7 °C, 80 % relative mean humidity and precipitation of 2632.7 mm (Weather Station: 769043 MMTP of the Water National Commission). The study included one year of sampling, from February 2011 until January 2012.

2.2. Biological material

The *Jatropha* Germplasm Bank contains 147 accessions of *J. curcas* collected in southern Mexico, from which 29 genotypes were selected (Table 1) based on average seed production from the years 2009 to 2013. Plants were selected from three groups that were established according to previous observations: with high seed production (> 0.5 kg plant⁻¹), medium amount (0.3-0.5 kg plant⁻¹) and low amount (< 0.3 kg plant⁻¹). The plants studied (five per genotype) had six years of age, were derived from cuttings (clones) and did not have any kind of cultural management.

Table 1. *Jatropha curcas* L. accessions collected in Southern Mexico and evaluated under common garden conditions.

Site of collection	Code	Number of accessions	Latitude (North)	Longitude (West)
Arriaga	(ARR)	3	16°11.231'	93°54.816'
Huixtla	(HUX)	4	15°05.115'	92°29.146'
Mapastepec	(MAP)	7	15°25.505'	92°53.854'
Suchiate	(SCH)	1	14°40.057'	92°10.071'
Tonalá	(TON)	1	16°03.430'	93°50.782'
Pijijiapan	(PIJ)	1	15°55.561'	92°59.842'
Puerto Chiapas	(PC)	1	14°43.742'	92°25.935'
Simojovel	(SIM)	1	17°08.312'	92° 42.438'
Pujilic	(PUJ)	1	16°16.430'	92°17.850'
Ciudad Cuauhtémoc	(CDCU)	3	15°40.473'	92°00.129'
Comalapa	(COM)	1	15°39.030'	92°08.170'
Piedra Ancha	(PA)	2	16°11.238'	97°44.825'
Ocozocautla	(OCZ)	1	16°46.243'	93°23.641'
Pinotepa Nacional	(PIN)	1	16°19.306'	97°53.564'
Guatemala Ciudad, C.A.	(GUA)	1	14°36.275'	90°29.083'

2.3. Evaluation of agronomic performance variables

Every 28 days each genotype was evaluated for plant height (m), stem diameter (cm), number of primary branches, number of inflorescences, ratio of male flowers to female, production cycles per year, damage by disease, pests or herbivory, number of ripe fruits, fruit weight (g), number of seeds, seed fresh weight (g), pulp fresh weight (g), seed dry weight (g) viviparity, fruit dehiscence. As the fruits were collected, representative samples were taken to determine their sphericity measuring (cm) length (Lm), diameter 1 ($Lp1$) and diameter 2 ($LP2$), to obtain the results using the formula: $S = \frac{(Lm * Lp1 * LP2)^{1/3}}{Lm}$.

For collected and stored seeds of each accession, the presence/absence of insects and percentage of oil were determined, using the 920.39 method of the Official Association of Analytical Chemists (AOAC, 1997). The variable potential of oil yield per area ($L\ ha^{-1}$) was obtained by multiplying the dry seed weight (kg) by 1200 plants per hectare, and the result was converted to oil ($kg\ ha^{-1}$) using oil production data of each accession. Finally, the result was expressed in volume (L), considering the oil density of *J. curcas*, which is $0.91\ kg\ L^{-1}$ (Ovando-Medina et al., 2011b).

2.4. Data analysis

The data were processed by multivariate analysis with the program XL-STAT© version 2012. For the selection of genotypes with better agronomic performance the technique of paired comparisons reported by Mishra (2009) was used. That technique weighs the variables according to their agronomic-productive importance (the researcher decides which variable is most important when compared to another), this value is called Preference Index (PI) for each pair of variables (Aij). Then we obtained the sum (Sj) of IP for each variable, by $Sj = \sum Aij$; to avoid negative values, a factor (F) is added, which is equal to the number of variables minus one ($F = n - 1$), obtaining the absolute weight (w) by the expression $w = Sj + F$. The relative weight of each variable (wj) is obtained by calculating the value $M = \sum (Sj + F)$ and the formula: $wj = \frac{(Sj+F)}{M}$.

With the relative weights, balanced scales were structured to qualify plants for each variable; thus, the highest value (equal to the relative weight) was the most desirable feature, and the lowest value the least desirable. Details are shown in Table 2.

The 29 accessions were rated according to the most important variables as detected by principal component analysis. For quantitative traits rating was made by comparisons between one accession in particular and the average of the rest of accessions, according to the following procedure: a) the percentage of superiority (s) of each trait per accession was obtained by the formula $s = (\text{single trait value} * 100) / \text{trait average in all accessions} - 100$; b) the corresponding score was given based on Table 2. For qualitative traits a score was assigned by trait and accession, based on Table 2. Finally, both quantitative and qualitative scores of each accession

were added together for the overall rating. Genotypes identified as outstanding were those that had the highest grades.

Table 2. Score for quantitative and qualitative characters of *Jatropha curcas* L. from the collection of the IBC Germplasm Bank (Universidad Autónoma de Chiapas, Mexico).

Quantitative		
Trait	Superiority (%)	Score
Plant height (2)	< 5	2
	5 - 30	1
	> 30	0
Stem diameter (3)	< 5	0
	5 - 30	1
	> 30	3
Number of primary branches (5)	< 5	1
	5 - 30	3
	> 30	5
Number of inflorescences (6)	< 5	2
	5 - 30	4
	> 30	6
Number of ripe fruits (8)	< 5	4
	5 - 30	6
	> 30	8
Pulp fresh weight (1)	< 10	1
	> 10	0
Number of seeds (10)	< 5	6
	5 - 30	8
	> 30	10
Seed fresh weight (10)	< 5	6
	5 - 30	8
	> 30	10
Seed dry weight (12)	< 5	8
	5 - 30	10
	> 30	12
Sphericity of the fruit (2)	< 0.90	1
	> 0.90	2
Oil content of the seed (12)	< 5	8
	5 - 30	10
	> 30	12
Potential of oil yield per hectare (13)	< 5	7
	5 - 30	10
	> 30	13
Qualitative		
Trait	Range	Score
Damage by diseases or pests (4)	Absence	4
	Minimal	3
	Moderate	2
	Advanced	1
	Severe	0
Production cycles per year (8)	Once	2
	Twice	4
	Three times	6
	Continuous	8
Fruit dehiscence (4)	Presence	0
	Absence	4

Numbers in parenthesis are the relative weights of the variables.

3. Results

3.1. Fruiting dynamics

The productive phenology study showed that production took place from February to November. Two major events were found where most of the accessions were in production, the first and most prominent was recorded in June and the second in August-September, with MAP-8 accession having the largest number of fruits (166) in the month of June (Figure

1). Both events were during the rainy season as shown in Figure 2. It could be noted that during the maximum precipitation (October) fruit production decreases, reaching values close to zero in the following months. The months of low fruit production correspond to the dry period from November to April. However, the analysis by accession showed that the kinetic behavior of production depends on the genotype studied.

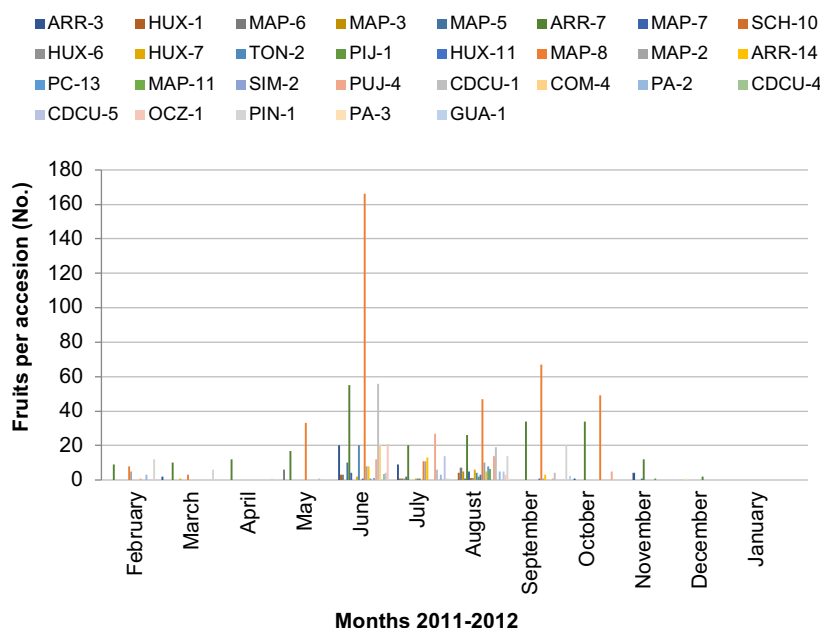


Figure 1. Production dynamics of 29 accessions of *Jatropa curcas* L. from the Germplasm Bank of the IBC of the Universidad Autónoma de Chiapas in the months of February 2011 to January 2012.

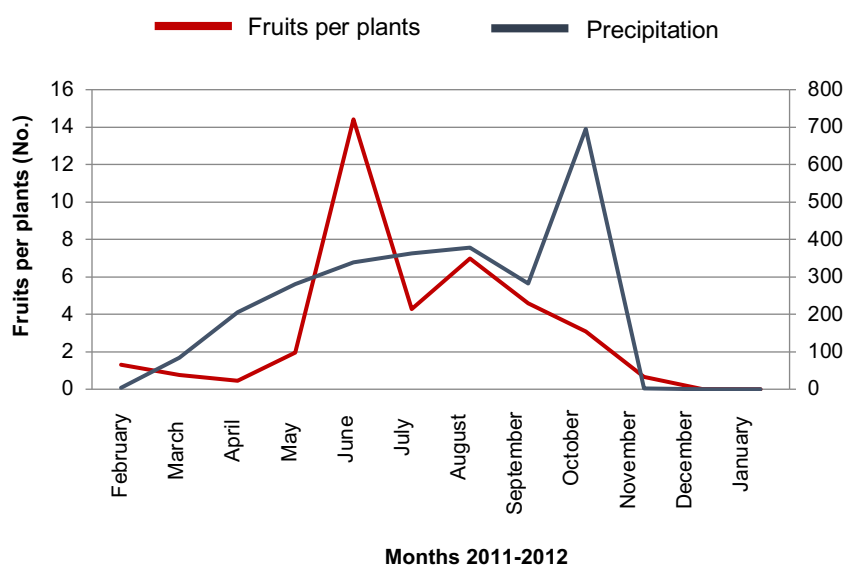


Figure 2. Relation of the production dynamics of *Jatropa curcas* L. and annual precipitation from February 2011 to January 2012 in Tapachula, Chiapas, Mexico.

Production cycle was defined as the lapse that occurs between an event of important flowering and the seed production stage, with duration of approximately three months. Based on the foregoing, the accessions were classified, finding that most had only one cycle, some two cycles (MAP-6, MAP-5, MAP-2, ARR-14, CDCU-1), three accessions had three cycles (MAP-8, PUJ-4, PIN-1) and only the accession ARR-7 presented four production cycles, i.e.,

continuous production. Although it only had three production cycles, accession MAP-8 was the most productive with 384 fruits throughout the year. Accessions with higher seed production during the sampling year were MAP-8 with 1341, ARR-7 with 1073, PIN-1 with 768, CDCU-1 with 256, PUJ-4 with 152, ARR-1 with 133, and MAP-2 with 114 seeds (Figure 3).

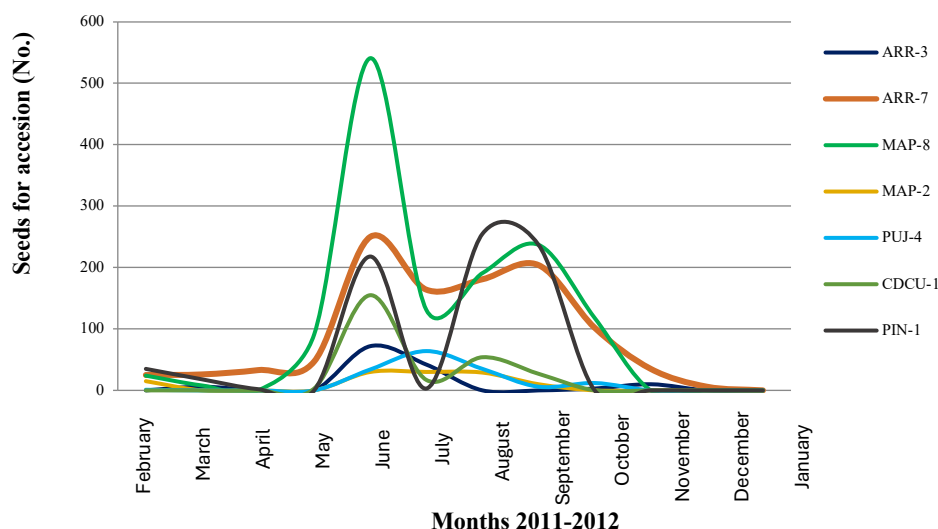


Figure 3. Accessions of the Germplasm Bank of the IBC that obtained the highest number of seeds of *Jatropha curcas* L. during the cycle February 2011 - January 2012.

3.2. Productive characterization

Table 3 presents the results of evaluated quantitative variables, showing initial and final data for these traits: height, stem diameter and number of branches; as well as final data for all other variables. The smallest increase in plant growth was observed in ARR-14 with only 7 cm (2.07 %), and the largest increase was shown by HUX-1 with 182 cm (58.14 %). Regarding stem diameter the greatest increase was CDCU-5 with 6 cm (66.66 %), accessions were found that did not have variation in the diameter of their stems. As for the number of primary branches, MAP-6 represented the largest increase in five branches (250 %) and plants were found that had not increased. The accession of MAP-8 showed 121 inflorescences, 384 fruits, 1341 seeds, a fresh pulp weight of 4089.34 g, fresh seed weight of 1253.94 g, dry seed weight of 1700.35 g, and oil yield potential of 895.02 L ha⁻¹. These values represent the greatest quantity in the different established variables. For every 4.09 male flowers there was a female flower (genotype PA-2), while the oil percentage range was between 31.04 % for genotype COM-4 to 50.55 % for CDCU-1.

In Table 4 presenting the qualitative variables, PIN-1 was the genotype most susceptible to disease, pests or herbivory. ARR-7 was the only genotype that presented fruit production throughout the year; only three genotypes presented dehiscence (ARR-7, ARR-14, and MAP-8), seven presented viviparity (MAP-6, MAP-3, ARR-7, HUX-11, MAP-8,

MAP-2, and PC-13), most genotypes showed storage pests (insects present), and genotypes with most spherical fruits were PA-2, PUJ-4, SIM-2, PC-13 and ARR-14.

3.3. Analysis of principal components

This analysis allows the reduction of variables and is used as one of several techniques to detect possible relationships between genotype backgrounds, including those of *J. curcas* (Zapico et al., 2011). Table 5 shows the values of the five major components, their percentage of variation and the percentage of cumulative variance. In this study the analysis reduced the original 18 traits into five main components which presented approximately 81.33 % of the total of cumulative variation. Principal component 1 (F1) which is the most important with an eigenvalue of 9.04 accounted for 50.27 % of the total variation, the variables with the highest values within F1 were productive cycles (CP), dehiscence (DE), number of inflorescences (NI), ripe fruit (NF), pulp fresh weight (MP), number of seeds (NS), seed fresh weight (MS), seed dry weight (MSS), plant height (H), stem diameter (DT), and oil potential yield (RPA). The principal component 2 (F2) with eigenvalue of 2.02 accounted for 11.27 % of the variance; the variables that contributed most to this factor were the number of primary branches (NR), sphericity (ES), disease or pest damage (DEP), and oil percentage (A).

Table 3. Productive variables of *Jatropha curcas* L. accessions from the collection of the IBC Germplasm Bank from February 2011 to January 2012.

Accession	H initial-final (m)	SD initial-final (cm)	BN initial-final	NI	RMF	DDP	PCY	NRF	PFW (g)	NS	SFW (g)	SDW (g)	S	D	V	IS	O (%)	PY (L ha ⁻¹)
ARR-3	3.13 - 3.55	16 - 19	2 - 2	35	3.18	3	1	36	477.5	133	127.1	107.9	0.98	0	0	1	37.18	52.88
HUX-1	3.13 - 4.95	10 - 10	2 - 2	30	2.43	3	1	8	72.71	25	22.2	19.6	0.92	0	0	0	43.62	11.27
MAP-6	3.38 - 3.50	15 - 15	2 - 7	27	1.41	3	2	17	166.1	60	59.2	44.9	0.87	0	1	0	40.86	24.19
MAP-3	3.90 - 4.00	10 - 15	3 - 4	46	2.34	3	1	6	57.9	24	19.7	18.9	0.90	0	1	0	42.81	10.69
MAP-5	3.46 - 3.70	9.5 - 13	2 - 6	47	1.90	3	2	14	147.3	47	38.3	31.8	0.92	0	0	0	46.71	19.59
ARR-7	4.00 - 4.20	14 - 20	3 - 5	108	1.92	3	4	231	2942.1	1073	815.1	848.4	0.94	1	1	1	39.65	443.62
MAP-7	3.58 - 3.75	9 - 10	3 - 4	9	1.37	3	1	9	91.9	53	34.0	38.1	0.87	0	0	1	44.20	22.20
SCH-10	4.50 - 4.90	15 - 17	4 - 4	11	0.93	3	1	1	11.6	3	4.0	3.6	0.90	0	0	0	42.30	2.26
HUX-6	2.51 - 2.72	10 - 12	3 - 4	26	0.49	3	1	1	7.1	3	4.3	3.7	0.92	0	0	0	49.37	2.82
HUX-7	4.38 - 4.60	14 - 16	2 - 3	47	1.18	3	1	10	111.7	49	38.3	41.6	0.94	0	0	1	45.96	25.20
TON-2	3.30 - 3.53	16 - 21	3 - 5	39	0.72	3	1	25	282.8	78	87.5	51.7	0.96	0	0	1	40.64	27.69
PIJ-1	3.42 - 3.85	14 - 15	2 - 4	59	1.17	3.5	1	4	32.9	31	9.7	18.8	0.80	0	0	1	49.43	12.24
HUX-11	3.00 - 3.28	10 - 12	2 - 2	33	1.68	3	1	5	37.7	13	13.9	15.1	0.92	0	1	1	50.02	9.97
MAP-8	4.41 - 4.70	24 - 26	2 - 3	121	2.24	2	3	384	4089.3	1341	1253.9	1700.3	0.92	1	1	1	39.92	895.02
MAP-2	3.61 - 4.00	8 - 9	2 - 3	36	1.26	3	2	35	365.6	114	126.3	88.4	0.91	0	1	1	45.79	53.35
ARR-14	3.38 - 3.45	10 - 10	3 - 5	15	1.02	4	2	29	338.3	89	86.2	60.2	0.99	1	0	0	43.16	34.25
PC-13	2.90 - 3.17	12 - 16	2 - 2	24	2.62	3.5	1	9	65.4	28	26.9	15.8	0.99	0	1	0	36.34	7.59
MAP-11	0.94 - 1.58	9 - 10	3 - 4	4	0.73	3	1	6	41.1	17	18.6	12.8	0.86	0	0	0	45.56	7.72
SIM-2	2.51 - 2.60	7 - 8	3 - 6	11	0.45	4	1	1	11.1	3	5.4	3.9	0.99	0	0	0	39.38	2.82
PUJ-4	3.17 - 3.38	13 - 14	2 - 3	54	2.79	3	3	60	725.7	152	178.8	114.4	0.99	0	0	1	36.83	55.54
CDCU-1	2.70 - 2.96	11 - 12	7 - 8	35	1.30	3	2	86	1004.8	256	287.9	169.5	0.95	0	0	1	50.55	112.96
COM-4	2.69 - 2.85	8 - 9	2 - 3	21	0.91	3	1	20	190.0	79	64.9	47.8	0.94	0	0	1	31.04	19.57
PA-2	3.67 - 3.90	11 - 16	3 - 6	19	4.09	3	1	11	118.0	37	31.7	25.1	0.99	0	0	0	41.50	13.75
CDCU-4	1.77 - 1.93	12 - 18	2 - 2	20	0.47	3	1	3	25.7	11	9.6	8.7	0.88	0	0	0	46.43	5.31
CDCU-5	2.47 - 2.85	9 - 15	3 - 4	36	1.73	3	1	23	201.3	61	68.5	42.6	0.98	0	0	0	35.54	19.97
OCZ-1	3.00 - 3.34	13 - 15	2 - 3	28	1.24	3	1	25	239.1	70	31.8	46.5	0.98	0	0	1	44.13	27.09
PIN-1	2.53 - 3.50	12 - 12	4 - 6	24	1.88	1.5	3	54	545.1	768	137.5	186.5	0.89	0	0	1	46.65	114.72
PA-3	2.32 - 3.65	8 - 8	2 - 3	29	0.52	3	1	2	14.3	9	5.1	5.4	0.91	0	0	0	45.82	3.28
GUA-1	1.65 - 1.95	12 - 14	2 - 4	6	1.22	3	1	2	16.2	7	5.9	5.2	0.98	0	0	0	43.07	2.97

H: plant height (m); SD: stem diameter (cm); BN: number of primary branches; NI: number of inflorescences; RMF: ratio of male to female flowers; DDP: damage by diseases or pests; PCY: production cycles per year; NRF: number of ripe fruits; PFW: pulp fresh weight (g); NS: number of seeds; SFW: seed fresh weight (g); SDW: seed dry weight (g); S: sphericity of the fruit; D: fruit dehiscence; V: viviparity; IS: Presence/absence of insects during the storage; O: oil content of the seed; PY: potential of oil yield per hectare.

Table 4. Qualitative variables of *Jatropha curcas* L. from the collection of the IBC Germplasm Bank, February 2011 - January 2012.

Accession	Damage by diseases or pests	Productive cycles	Presence/absence of dehiscence	Presence/absence of viviparity	Presence/absence of insects	Sphericity of the fruit
ARR-3	3.00	1	0	0	1	0.98
HUX-1	3.00	1	0	0	0	0.92
MAP-6	3.00	2	0	1	0	0.87
MAP-3	3.00	1	0	1	0	0.90
MAP-5	3.00	2	0	0	0	0.92
ARR-7	3.00	4	1	1	1	0.94
MAP-7	3.00	1	0	0	1	0.87
SCH-10	3.00	1	0	0	0	0.90
HUX-6	3.00	1	0	0	0	0.92
HUX-7	3.00	1	0	0	1	0.94
TON-2	3.00	1	0	0	1	0.96
PIJ-1	3.50	1	0	0	1	0.80
HUX-11	3.00	1	0	1	1	0.92
MAP-8	2.50	3	1	1	1	0.92
MAP-2	3.00	2	0	1	1	0.91
ARR-14	4.00	2	1	0	0	0.99
PC-13	3.50	1	0	1	0	0.99
MAP-11	3.00	1	0	0	0	0.86
SIM-2	4.00	1	0	0	0	0.99
PUJ-4	3.00	3	0	0	1	0.99
CDCU-1	3.00	2	0	0	1	0.95
COM-4	3.00	1	0	0	1	0.94
PA-2	3.00	1	0	0	0	0.99
CDCU-4	3.00	1	0	0	0	0.88
CDCU-5	3.00	1	0	0	0	0.98
OCZ-1	3.00	1	0	0	1	0.98
PIN-1	1.50	3	0	0	1	0.89
PA-3	3.00	1	0	0	0	0.91
GUA-1	3.00	1	0	0	0	0.98

As for principal component 3, the variable that contributed most to it was the ratio of female to male flowers (RFM) with an eigenvalue of 1.38 % to 7.68 % variation. While components 4 and 5 with very low eigenvalues only accounted for a very low 6.78 % - 5.35 % of the total variance.

Table 5. Eigenvalue of the five main components of *Jatropha curcas* L. from the collection of the IBC Germplasm Bank, obtained from 18 variables of agronomic performance.

Component	Total	% of variation	% cumulative variance
1	9.049	50.274	50.274
2	2.029	11.272	61.547
3	1.383	7.683	69.229
4	1.221	6.783	76.012
5	0.964	5.358	81.370

For further analysis only the variables with high values in the F1 and F2 were considered. The diagram of genotype distribution of the principal component analysis was formed in accordance with principal component 1 and principal component 2 (F1 and F2) which together account for 61.54 % of the variance. In Figure 4 shows the formation of three main groups, which are separated from each other since they

are different among them, even though the genotypes forming each group are very similar to each other. The largest group contains genotypes with low to medium levels of production, while the other groups contain the most productive genotypes, especially on the right side consisting of ARR-7 and MAP-8.

3.4. Rating of genotypes by paired comparisons

This technique allows for weighing the variables according to their agronomic-productive importance which served to decide which variable is more important than another, correlating the variables of the X axis against the Y axis (Table 6). Thus, number 1 was assigned to the most important, 0 if they are equally important and -1 to the least important. This with the objective of obtaining the relative weights of each variable, which represents the data for rating plants by each variable. Table 7 shows the results of relative weights (P.R.) obtained on all variables. Oil potential yield (RPA) was found to be the most important variable, with P.R. 13, followed by percentage of oil (A), seed dry weight (MSS) with P.R. 12 and ripe fruits (NF), seed fresh weight (MS) with P.R. 10. The least important variables were pulp fresh weight (MP) with P.R. 1, plant height (H) with P.R. 2 and stem diameter (DT) with P.R. 3.

Table 6. Scores for selection of outstanding genotypes of *Jatropha curcas* L. from the IBC Germplasm Bank.

	Characteristic	Plant in evaluation		Pair plants		Accession (n)	Average
		MAP-8	HUX-1	MAP-6	MAP-3		
Quantitative variables	H (m)	4.55	3.09	3.41	3.50		6.45
	SD (cm)	24.55	10.00	15.00	11.55		12.73
	BN	2.75	2.00	4.67	3.00		3.14
	NI	121.00	30.00	27.00	46.00		34.72
	NRF	384.00	8.00	17.00	6.00		38.41
	PFW (g)	4089.34	72.71	166.08	57.97		428.59
	NS	1341.00	25.00	60.00	24.00		160.10
	SFW (g)	1253.94	22.20	59.24	19.75		124.50
	SDW (g)	1700.35	19.60	44.90	18.94		130.34
	O (%)	39.92	43.62	40.86	42.81		42.91
Superiority (%)	PY (L ha ⁻¹)	895.02	11.27	24.19	10.69		70.36
	H (m)	-29.46	-52.09	-47.13	-45.74		
	SD (cm)	92.83	-21.44	17.84	-9.30		
	BN	-12.44	-36.32	48.58	-4.48		
	NI	248.46	-13.60	-22.24	32.47		
	NRF	899.64	-79.17	-55.75	-84.38		
	PFW (g)	854.15	-83.03	-61.25	-86.48		
	NS	737.59	-84.38	-62.52	-85.01		
	SFW (g)	907.19	-82.17	-52.42	-84.13		
	SDW (g)	1204.54	-84.97	-65.55	-85.47		
Points per variable	O (%)	-6.98	1.64	-4.78	-0.25		
	PY (L ha ⁻¹)	1172.02	-83.98	-65.61	-84.81		
	H (m)	2	2	2	2		
	SD (cm)	3	0	1	0		
	BN	1	1	5	1		
	NI	6	0	0	6		
	NRF	8	4	4	4		
	PFW (g)	0	0	0	0		
	NS	10	6	6	6		
	SFW (g)	10	6	6	6		
Qualitative variables	SDW (g)	12	8	8	8		
	O (%)	8	8	8	8		
	PY (L ha ⁻¹)	13	7	7	7		
	DDP	3	3	3	3		
	PCY	6	2	4	2		
Rate (points from 1 to 100)	D	0	4	4	4		
	S	2	2	1	2		
Rate (points from 1 to 100)		84	53	59	59		

Of the 18 variables assessed, the principal component analysis reduced them to 15. Table 8 shows an example of paired comparisons for selecting outstanding *J. curcas* genotypes. For quantitative traits rating was made by comparisons between one accession (e.g. MAP-8) and the average for the rest of accessions, according to the procedure described in the Materials and Methods section. After adding the quantitative and qualitative scores of each accession to obtain the overall rating, the most outstanding genotypes were identified as those which had the highest ratings, highlighting ARR-7 and CDCU-1 (Table 8).

4. Discussion

The study of traits of agronomic importance is considered a useful tool for the selection of candidate genotypes for commercial planting. In this regard, the results of this work can be taken as a starting point for the identification of genotypes of *J. curcas* that could be used for extensive cultivation, provided they are further evaluated in different planting schemes.

Two of the three components of the research (the productive characterization and clustering of accessions) were compared with those reported in the literature, as there is an accumulation of information on the phenology and diversity of accessions of *J. curcas* in recent years (Achten et al., 2010;

Carels 2009; Divakara et al., 2010; Ovando et al., 2011c). Meanwhile, on the issue of selection of genotypes for paired comparisons of *J. curcas* no reports were found in scientific

literature, although some reports mentioned implicitly plant selection, but without following a procedure specifically designed for this purpose.

Table 7. Matrix for the weighting of agronomic-productive variables of *Jatropha curcas* L. from the IBC Germplasm Bank, based on the method of paired comparisons (Mishra, 2009).

		Variables (X)														
		H	SD	BN	NI	DDP	PCY	NRF	PF W	NS	SF W	SD W	S	O	PY	DE
Variables (Y)	H	—	1	1	1	0	1	1	-1	1	1	1	0	1	1	1
	SD	-1	—	1	1	0	1	1	-1	1	1	1	-1	1	1	1
	BN	-1	-1	—	1	0	1	1	-1	1	1	1	-1	1	1	-1
	NI	-1	-1	-1	—	0	0	1	-1	1	1	1	-1	1	1	-1
	DDP	0	0	0	0	—	1	1	0	1	1	1	0	1	1	1
	PCY	-1	-1	-1	0	0	—	1	-1	1	1	1	-1	1	1	-1
	NRF	-1	-1	-1	-1	-1	-1	—	-1	1	1	1	-1	1	1	-1
	PFW	1	1	1	1	0	1	1	—	1	1	1	0	1	1	1
	NS	-1	-1	-1	-1	-1	-1	-1	-1	—	1	1	-1	1	1	-1
	SFW	-1	-1	-1	-1	-1	-1	-1	-1	0	—	1	-1	0	1	-1
	SDW	-1	-1	-1	-1	-1	-1	-1	-1	0	-1	—	-1	0	1	-1
	S	0	1	1	1	0	1	1	0	1	1	1	—	1	1	0
	O	-1	-1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	—	1	-1
	PY	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	—	-1
	DE	-1	-1	1	1	0	1	1	-1	1	1	1	0	1	1	—
	$S_j=\sum A_{ij}$	-10	-7	-3	0	-6	3	4	-12	8	8	10	-10	12	14	-5
$S_j + F$	4	7	11	14	8	17	18	2	22	22	24	4	26	28	9	
Relative weight	2	3	5	6	4	8	8	1	10	10	12	2	12	13	4	

H: plant height (m); SD: stem diameter (cm); BN: number of primary branches; NI: number of inflorescences; DDP: damage by diseases or pests; PCY: production cycles per year; NRF: number of ripe fruits; PFW: pulp fresh weight (g); NS: number of seeds; SFW: seed fresh weight (g); SDW: seed dry weight (g); S: sphericity of the fruit; O: oil content of the seed; PY: potential of oil yield per hectare; D: fruit dehiscence.

$S_j = \sum A_{ij}$: Sum of the index of preference for each variable

F: factor to avoid negative values; equal to the number of variables minus one.

See the text for details.

Although there were no reports of fruit production dynamics, Aker (2012) mentions that the months with the highest flowering of *J. curcas* grown in Nicaragua in the 1994-1995 cycle were April, May, June and August. Considering that the time from flowering to fruit formation is approximately two months, it follows that fruiting occurred in the months of June, July, August and October, coinciding with the results of this study. Another study with similar results is that of Jøker and Jepsen (2003) who conducted a study in Africa and say that flowering occurs during the season with scarce rainfall, noting that the months of April, May and June are the only ones where this stage is achieved; therefore, fruit production would be presented in the months of June, July, August and September. By contrast, studies of flowering (from which fruit production can be deducted) related to germplasm grown in India show periods other than what was found in this research; in this sense, Bhattacharya et al. (2005) found that the flowering period is from July to September; Sukarin et al. (1987) observed two flowering peaks, one in November and one in May, mentioning that in wet conditions the plant flowers all year; Kaur et al. (2011) observed two stages of flowering under subtropical conditions, the first began in the third week of April and

ended on the fourth week of June, and the second began on the second week of July and finished on the second week of November. These differences mentioned may be due to environmental conditions, particularly to soil moisture, in the sites where plants are grown.

Table 8. Outstanding/low-performance genotypes of *Jatropha curcas* L. from the IBC Germplasm Bank according to the method of paired comparisons.

Outstanding genotypes		Lower-performing genotypes	
Accession	Score	Accession	Score
ARR-7	88	MAP-, MAP-11	55
CDCU-1	85	HUX-1, COM-4, GUA-1, OCZ-1	56
MAP-8	84	ARR-14	57
PIN-1	81	HUX-6, HUX-11, ARR-3, PC-13, PA-2, CDCU-4, PA-3	58

With regard to the number of fruits per plant, Machado (2011) reports a productivity ranging from 2 to 102 fruits in a study of *J. curcas* plants one year of age grown in Cuba; this differs from the findings in this study, since it presented a production of 1-384 fruits taking into account that the plants

studied were 3 years of age, it also differs from the data reported by Gohil and Pandya (2009) who found a production of 4.7 to 55.3 in *J. curcas* plants of one and a half years of age grown in India; likewise it reported that the number of seeds was found in a range of 10.66 to 63 with large difference to that found in this study which was from 3 seeds to 1341. Kaushik et al. (2007) conducted a study of *J. curcas* collected from different agroclimatic zones of the state of Haryana, India, finding the weight of 100 seeds in a range of 69.20 g to 49.20; in this study the range obtained was 77.50 g to 126.79 g, data similar to those reported by Machado (2011) with 72.3 g to 106.2 g. Distinct data are reported by Saikia et al. (2009), in a study conducted in India, where they found a range of 40 to 142 g. As for the percentage of oil published data are quite varied, for example, Gohil and Pandya (2009) reported 8.1 % to 30.6, while Kaushik et al. (2007) of 28 % to 38.8. Machado (2011) found from 32.8 to 35.0 % and in this study, it was 31.04 % to 50.55 %.

Machado (2011) reported plant height in a range of 82.2 to 240.5 cm, the number of primary branches 2 to 10 and stem diameter 3.80 to 7.50; for their part, Gohil and Pandya (2009) found that the plant height ranges from 119.43 cm to 159.2 cm, the number of primary branches 2.8 to 25 and stem diameter 12 to 17.2, while in this study, plant height ranges from 98.87 to 400.55 cm, the number of primary branches of 2 to 7.33 and stem thickness is 8 to 24.55 cm. Saikia et al. (2009) reported the plant height of 72.67 to 280 and the number of primary branches from 2 to 11 on an evaluation of *J. curcas* plants two years of age.

Relating to the variables of seed mass, Machado (2011) reported between 37.3 g and 325.6 g, which corresponds to a seed potential yield per hectare of 93.2 to 814 kg. These data differ from what was found in this study, since it was found that seed mass was 3.60 to 1700.35 g and the seed yield potential per hectare of 4.86 to 2040.42 kg; this is evidence that the Mesoamerican accessions are more diverse than those of other parts of the world.

The analysis of principal components has been used as one of several techniques to detect possible relations between provenances of genotypes, including those of *J. curcas*. In this study the analysis reduced the original 18 traits into five main components representing approximately 81.37 % of the total cumulative variation; similar data are reported by Zapico et al. (2011) who carried out a study of the phenotypic diversity of *J. curcas*, evaluating 21 quantitative traits of 13 accessions from the Philippines where they found the 88.81 % of the total variation accumulated for the first five principal components. They found that the F1, which was the most important component, accounted for 37.25 % of the total variation and the variables that contributed most to this factor were: number of leaves, height during the seedling stage and after transplanting to the field, the germination rate, survival, and weight of the fruit pulp. Unlike Machado (2011), who characterized morphologically and productively 15 accessions from Cuba, evaluating 16 traits. He found that F1 accounted for 57.7 % of the total variation and variables

that formed this factor were: plant height, the thickness of the primary branches, number of secondary branches, number of primary branches and stem diameter in base.

The selection procedure for paired comparisons is considered more suitable than others that have been published in scientific or commercial media, because the assessment was carried out in plants derived from clonal propagation and therefore its origin is certain; they were in common garden conditions, which thereby eliminated the environmental effect and, therefore, differences between accessions were due more to genes than to the environment; they were three years of age and were in production since the first year of cultivation, so it was noted that they had reached their productive potential; additionally, the method only considered statistically important variables and included 11 quantitative and four qualitative traits. In comparison, Sunil et al. (2008) studied *J. curcas* plants from five to 10 years of age *in situ* in four areas of the state of Haryana, India, and based on the method described by Zangemeister (2014) to select genotypes they found that the promising accessions were three: IC537924, IC537939 and IC541650 with 40 points and the accession with the lowest score was IC544675 with 34 points. It is noteworthy that by performing the study *in situ* the environment had an influence on the phenotypic characteristics recorded, in addition they considered few variables (eight quantitative and one qualitative: plant health), but have the advantage of having studied plants of at least five years of age, which ensures that production has stabilized.

Some companies have started marketing *Jatropha* genotypes either derived from processes of selection or hybridization, although they have not made public the methods of obtaining these genotypes, as in the case of the hybrids from SDAUJ® (Basha and Sujata, 2007), JMax™ (Eswaran and Johnson, 2012).

In conclusion, growing “piñón” has attracted much interest and enthusiasm in governments and institutions around the world, however, the massive establishment of commercial plantations is being made without considering many aspects of biology, ecology and agronomic management of the plant, which could lead to unsustainable production practices. The results of this study contribute to the selection of candidate genotypes for planting in the field but will require further evaluation in the context of environmentally friendly practices, and their response to organic fertilization and cultivation in different agroforestry arrangements.

Conflict of interests

The authors declare no conflict of interest.

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