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EFFECT OF DIFFERENT SPATIAL ARRANGEMENTS OF *Jatropha curcas* L. ON FOOD CROPS

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ABSTRACT

The objective of this study was to assess, during three years, the spatial arrangement that will enhance the morpho-productive development of *Jatropha curcas* L. in association systems with staple crops. It was hypothesized that the association of crops is a factor that determines the behavior of the species and the development of agroenergetic farms, considering rainy and low rainfall periods. A quasi-experimental design was used, and four treatments were tested: 1) *J. curcas* (Jc) in monoculture; 2) 50 % of the area with Jc and 50 % planted with food crops in rotation (CA); 3) Jc intercropped with CA; and 4) area planted with CA. A principal component statistical analysis was performed with the variables fruit yield and associated crop yield using 95 % confidence intervals from a Student's t-test. The number of bunches and total fruit and seeds harvested from Jc were shown to be the most important and had a positive correlation for the first component in each period. As for fruit yield, the highest values were achieved in monoculture. Although high yields were not attained in CA, the relationship is regarded favorable since the use of polycultures is viable, fundamentally in the arrangement of 50 % Jc + 50 % CA, being positive the biological efficiency given by the diversification and the best equivalent land use.

Keywords: monoculture, intercropping, agroecosystem, food security.

INTRODUCTION

Jatropha curcas L. belongs to the *Euphorbiaceae* family and is a perennial shrub native to Central America (Mitra *et al*., 2021). The seeds of this species have a high oil content. They are considered non-edible due to the presence of toxic compounds harmful to humans and animals (Zimila *et al*., 2021). This oil can be used to produce biofuel and other by-products. In addition, the residual cake after being detoxified can be used for feeding different animal species and the husk as a source of energy due to its caloric potential (Figueroa-Saavedra *et al*., 2020).

Several authors (Valdés-Rodríguez *et al*., 2013; Ávila-Soler *et al*., 2018) highlight that *J. curcas* supports land reclamation and develops in different soils and agroclimatic conditions, with seed yields varying between 0.5 and 5 Mg ha^{-1} per year. However, after a decade of studies on the species, this information is considered imprecise and heterogeneous. Abobatta (2019) emphasizes that *J. curcas* is still in the process of domestication, that its behavior is similar to that of other perennial crops, and that to reach peak production, it is necessary to take into account varietal selection, certain specific soil, climate, and agronomic management conditions.

Among the factors to be considered in agronomic management, plant density is one of the elements that most influence agricultural yield. All crops require an optimal area to capture adequate light energy that favors photosynthesis and increased leaf growth, which can lead to increased productivity (Alvarado-Ramírez *et al*., 2022). Different planting densities are used in plantations of *J. curcas*, depending on the objectives pursued. In monoculture of the species, up to 5000 plants ha^{-1} have been used (Góngora-Canul *et al*., 2018). Other low densities are also used, fundamentally in association systems with food crops, which is a practice based on the policies of environmental sustainability and food security, since diverse products are obtained in the same space and better use is made of the soil.

Müller *et al*. (2014) determined a greater development of crown diameter and number of *J. curcas* shoots when using 6 x 3 m spacings in two types of associations: agrosilvopastoral (maize-*Brachiaria-Jatropha* integration) and silvopastoral (*Brachiaria-Jatropha* integration). On the other hand, in studies conducted in Mexico by Rucoba-García and Munguía-Gil (2013), when comparing two production systems of *J. curcas* in monoculture and in association with *Zea mays* L. and *Phaseolus vulgaris* L., it was possible to determine the economic profitability of intercropping the tree with these crops. It was demonstrated that with intercropping, the profits were slightly higher than those obtained with monocultures.

In Cuba, research has been carried out on the association of more than twenty food crops, in which considerable production has been achieved, mainly of beans (*P. vulgaris* L.), soybeans (*Glycine max* (L.) Merr.), peanut (*Arachis hypogaea* L.), corn (*Z. mays* L.), cassava (*Manihot esculenta* Crantz), and sorghum (*Sorghum bicolor* (L.) Moench), with average productivity rates of 3.5 kg of fruit per tree of *J. curcas* (Sotolongo-Pérez *et al*., 2007), which has made it possible to assess the adaptation of the plant to the soil and climatic conditions of the country, to be considered in production systems from the inclusion in agroenergy farms. However, the results of these studies are diverse, and in many cases, the yields represent unreliable extrapolations.

The aim of this study was to assess the spatial arrangement that will enhance the morpho-productive development of *J. curcas* in association with food crops. Under the hypothesis that spatial distribution is one of the agronomic management factors that determine the morpho-productive behavior of *J. curcas* associated with food crops, its study will allow the evaluation of the most appropriate variants for the development of agroenergetic farms.

MATERIALS AND METHODS

Geographical location and experimental period

The experiment was conducted at the Experimental Station of Pastures and Forages "Indio Hatuey" (22° 48′ 7″ N and 81° 2′ W), at 19.01 m altitude, in the municipality of Perico, Matanzas province, Cuba. The experiment lasted for three years, from November 2016 to October 2019.

Edaphoclimatic characteristics

The experiments were established on a flat topography soil with a slope of 0.5 to 1 % and of the genetic type Ferrallitic Red Leached (Hernández-Jiménez *et al*., 2015). The average depth to bedrock is 150 cm. The climate is classified as tropical sub-humid (Inzunza, 2005) and has two seasons defined by rainfall: the low rainfall period (PPLL) from November to April, and the rainy period (PLL) from May to October (Academia de Ciencias de Cuba, 1989).

During the experimental period (2016–2019), the yearly average temperature was above 24.1 °C. The precipitation volumes in 2018 were above the historical average (Figure 1). Data were taken from the Agrometeorological Station "Indio Hatuey" 78329, attached to the Institute of Meteorology (INSMET, 2016) and located at 19.9 m altitude in the municipality of Perico, Matanzas province, Cuba (22°, 48′, 7′′ N and 81° 2′ W).

Experimental procedure for *J. curcas*

J. curcas was planted three years before the start of the study to ensure stability in plant production (Lama *et al*., 2018). The soil was prepared conventionally (two plowing rounds were interspersed with two harrowing rounds), with an interval between tillages of approximately 20 days. Subsequently, two seeds from Cabo Verde were deposited in each hole. One year before the experiment, a homogenization cut was made, pruning at 10 cm above the base of the soil to remove the apical meristem and favor axillary branching and a greater quantity of fruits in all plants (Valdés-Rodríguez *et al*., 2020). On the other hand, food crops were intercropped between the *Jatropha* furrows: beans (*Phaseolus vulgaris* L.), sweet potatoes (*Ipomoea batatas* (L.) Lam.), and squash (*Cucurbita moschata* Duch), which were planted at different times, taking into account the climatic requirements of each species (Figure 2), and were associated according to the spatial arrangements that were evaluated.

In all cases, for the planting of food crops, soil preparation was carried out prior to planting, and two plowing and two harrowing operations were performed. For this, the technical standard for each crop (MINAG, 2012) was taken into account, and the agronomic variables necessary to estimate yield were evaluated.

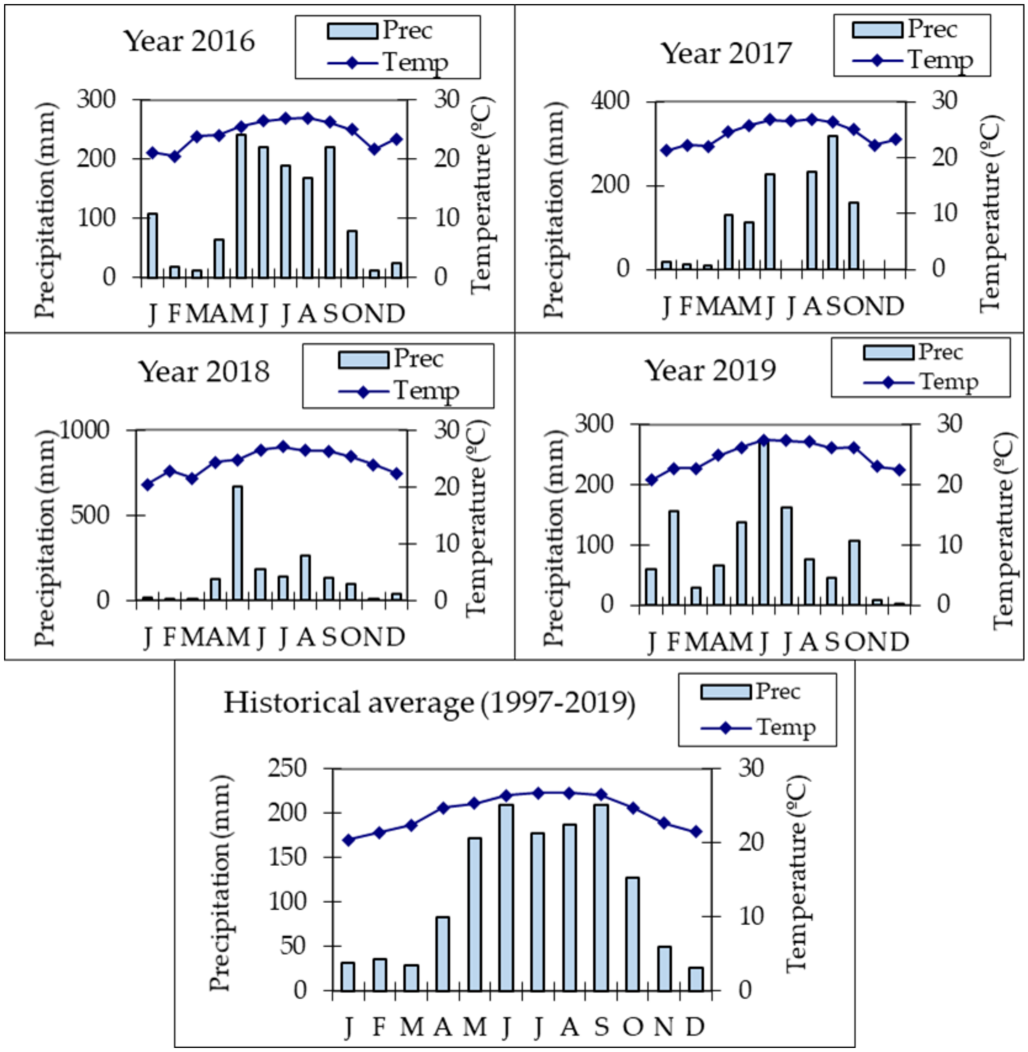

Figure 1. Behavior of climatic elements (mean temperature and precipitation) during the experimental period recorded at the Indio Hatuey Agrometeorological Station (INSMET, 2016).

Treatments and experimental design

Four treatments were studied (Table 1), and a quasi-experimental model was used as the treatments were applied in non-randomized plots (Curbeira-Hernández *et al.*, 2017). This design is employed when random assignment is impossible, and its purpose is to test the existence of a causal relationship between two or more variables (Bono-Cabré, 2012). For this, 15 *J. curcas* plants were considered replicates in each plot. The treatments were assigned as follows: T1, *J. curcas* (Jc) in monoculture, sown at 2.5 m between rows and 2 m between plants, composed of ten rows; T2, 50 % of the area with Jc sown at 2.5 m between rows and 2 m between plants, composed of five

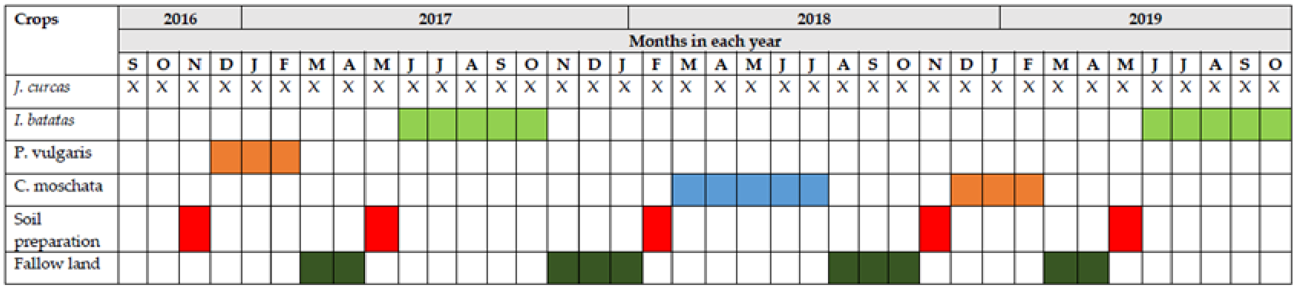

Figure 2. Period schedule of food crops associated with *Jatropha curcas* L. S: September; O: October; N: November; D: December; E: January; F: February; M: March; A: April; M: May; J: June; J: July; A: August.

Table 1. Jatropha curcas intercropping treatments with food crops.

Treatment	Spatial arrangement	Crop type	Evaluation year
T1	*J. curcas* in monoculture	-	2016–2019
T2	50 % *J. curcas* and 50 % with rotational cropping	Beans Sweet potato Squash	2016 and 2018 2017 and 2019 2018
T3	*J. curcas* intercropped with crops	Beans Sweet potato Squash	2016 and 2018 2017 and 2019 2018
T4	With food crops in rotation	Beans Sweet potato Squash	2016 and 2018 2017 and 2019 2018

rows and 50 % of the area sown with different food crops in rotation (Figure 2); T3, Jc sown at 5 m between rows and 2 m between plants, composed of five rows of the tree crop, intercropped with food crops in rotation; and T4, area sown with food crops in rotation. The factor under study was the spatial arrangement, which was evaluated to introduce *J. curcas* in different agroenergy systems (Figure 3).

Characteristics of association crop planting

In the case of beans, seeds of the Cuba-Cueto 25-9 black variety were used. Planting was done directly in the field, at 0.7 m between rows and 0.05 m between plants. Harvesting was done manually after 90 days (MINAG, 2012). For sweet potato, the INIVIT B 98-2 variety was used. Planting was carried out in the months of June 2017 and 2019 from cuttings of 25 to 30 cm in length, which were planted at 0.9 m between rows and 0.3 m between plants. Harvesting was carried out after 150 days, including all tubers (MINAG, 2012).

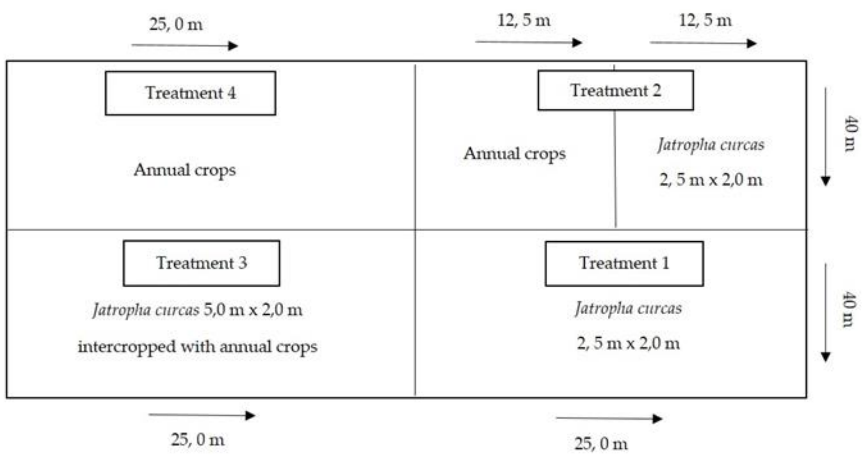

Figure 3. Distribution of the spatial arrangements (treatments) in the field.

Squash was planted in March 2019. Planting was done at 5 x 1 m between plants. The INIVIT C-88 variety was used. At sowing, two seeds were deposited per hole. When the plants had 2 to 3 leaves per plant, thinning was carried out, and the weakest plant was eliminated in each case. Harvesting took place after 120 to 150 days, when the fruits reached physiological maturity, that is, when the part in contact with the soil turned yellow (MINAG, 2012).

Evaluations in the cultivation *of J. curcas*

The evaluations were carried out each year, considering the two fruiting periods of *J. curcas* in the climatic conditions of Cuba, which are from July to September and from December to February, that coincide with the rainy and low rainfall periods. To carry out the morphological and productive measurements, the methodology proposed by Campuzano-Duque (2009) was used as a basis.

Morphological variables of *Jatropha*

The morphological variables were measured in each rainy period of each year when the plant began the reproductive phase: one month before each fruiting, in June (PLL), and November (PPLL). The variables recorded were: height (A), taken from the base of the plant to the apex of the main stem using a graduated ruler; stem thickness (GT) at a height of 10 cm from the soil surface, measured with a tape measure; crown diameter (DC), recording the horizontal length projected by the crown of the tree on the ground using a tape measure; and number of branches (NR), counting the number of branches inserted from the main stem.

Production variables of *Jatropha*

Harvesting was carried out in a staggered manner, as the fruits became yellow or black in color. Harvesting was carried out from July to September (PLL) and from December to February (PPLL) of each year. The following variables were counted: number of clusters (CR) formed on each plant; total fruit harvested (TFC), where the number of harvests in each period was determined by the level of fruit ripening; total seeds harvested (TSC), considering the number of seeds that each harvested fruit had per plant; and fruit yield (RF), considering the number of harvested fruits, their weight, and the number of plants per hectare.

Production variables of food crops

Yield was calculated considering five samples in each strip as replicates. The size of each sample was one linear meter and two furrows in beans and sweet potato, and for squash, it was a single furrow. In all cases, yield was calculated in Mg ha^{-1} from the sowing or planting frame used.

The biological efficiency of polyculture use was calculated to determine the feasibility of each spatial arrangement. For this purpose, the equivalent land use index (UET) was taken into account using the equation proposed by Casanova *et al*. (2001):

$$UET = Px / Ux + Py / Uy$$

where Px is the yield of crop x in polyculture, Ux is the yield of crop x in monoculture, Py is the yield of crop in polyculture, and Uy is the yield of crop in monoculture. If $UET > 1$, polyculture is advantageous; if $UET < 1$, it is not advantageous; and if $UET = 1$, the way of planting is indifferent.

Statistical analysis

For the data obtained, the relationship between morphological and productive variables was analyzed using multivariate statistics. For this purpose, the principal component analysis method was used, and the results were represented through a Biplot graph (Gabriel, 1971), where the treatments were plotted considering in each case the three years of evaluation and, within these, the PPLL and PLL periods. The fruit yield and associated crop yield variables were analyzed by descriptive statistics, using 95 % confidence intervals with the t-Student test statistic. The analyses were performed using the statistical package InfoStat 2008 (di Rienzo *et al*., 2011).

RESULTS AND DISCUSSION

The principal components of morphological and productive variables in *J. curcas*, as a result of different spatial arrangements in the first year of evaluation, are shown (Figure 3). During the PPLL, 100 % of the variance was explained (Figure 4A). The first component (CP1) extracted 61.5 % and height (A), stem thickness (GT), number of clusters (CR), total fruit (TFC), and harvested seeds (TSC) contributed to its formation, which were positively related, and the highest values were reached with the *Jatropha* monoculture (T1).

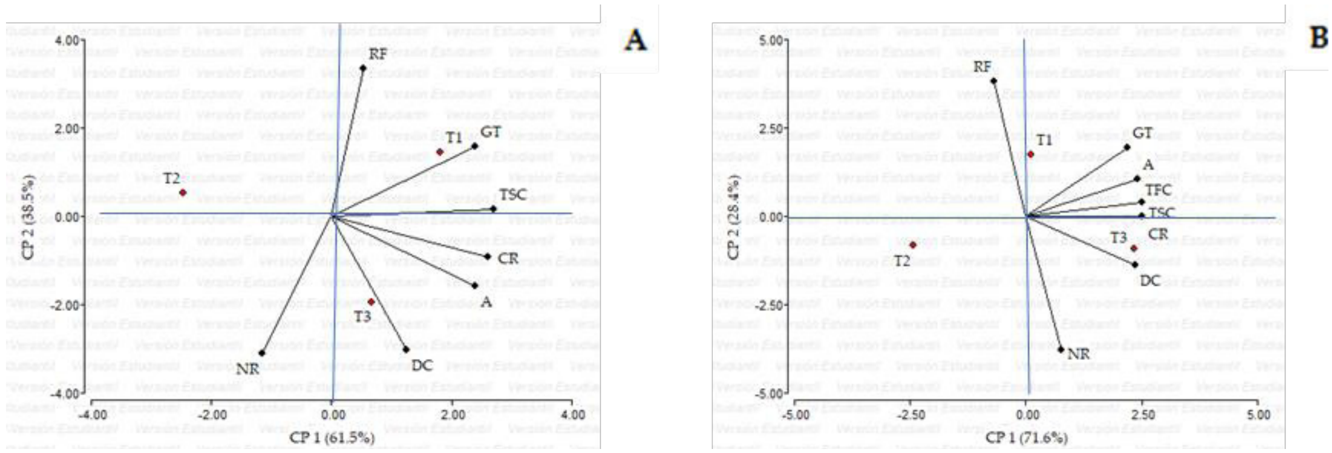

Figure 4. Principal component analysis (biplot graph) of morphological and productive variables by effect of spatial arrangements in *Jatropha curcas* L. in the first year of evaluation. A: low rainfall period (PPLL); B: rainy period (PLL). T1: Jc monoculture; T2: 50 % Jc + 50 % food crop; T3: Jc intercropped with food crop; A: height; DC: crown diameter; GT: stem thickness; NR: number of branches; CR: number of clusters; TFC: total fruits harvested; TSC: total seeds harvested; RF: fruit yield.

In the second component (CP2), a 38.5 % variance was detected, mainly explained by the fruit yield (RF) variables, and negatively related to the number of branches (NR) and crown diameter (DC); the highest values for the latter were reached when *J. curcas* was intercropped with food crops (T3), while for RF they were with T1.

For PLL, 100 % of the total variance was explained (Figure 4B). CP1 (71.6 %) was explained by A, DC, GT, CR, TFC, and TSC. For these variables, the highest values were obtained with T3. The variability extracted in CP2 was 28.4 % and is explained by RF and NR, which were negatively related. For RF, the highest values were found with the control treatment used for the tree (T1).

In the biplot representing the PPLL of the second year of evaluation (Figure 5A), a cumulative variance of 100 % was obtained. In CP1, a close positive relationship was detected between A, DC, NR, CR, TFC, and TSC. The highest values for these variables were found when using *J. curcas* intercropped with the associated crops (T3). In CP2 (29 % of the total variance), there was a negative correspondence between GT and RF, for which the highest values were reached with T1 (*J. curcas* in monoculture).

For PLL, 100 % of the total variance was also explained (Figure 5B). From CP1, 61.3 % was extracted. The variables that best explained this percentage were A, CR, TFC, and TSC, for which the highest values were reached when using *J. curcas* intercropped with food crops (T3). CP2 explained 38.7 % of the variance, and DC, NR, and, in the opposite direction to these variables, GT and RF interacted. For the latter, the highest values were found when using *J. curcas* in monoculture (T1).

In the low rainfall period of the third year of evaluation (Figure 6A), the total accumulated variance was again high at 100 %. For CP1 (76 %), the variables A, NR, CR, TFC, TSC, and GT contributed to fruit yield and were negatively related to the other

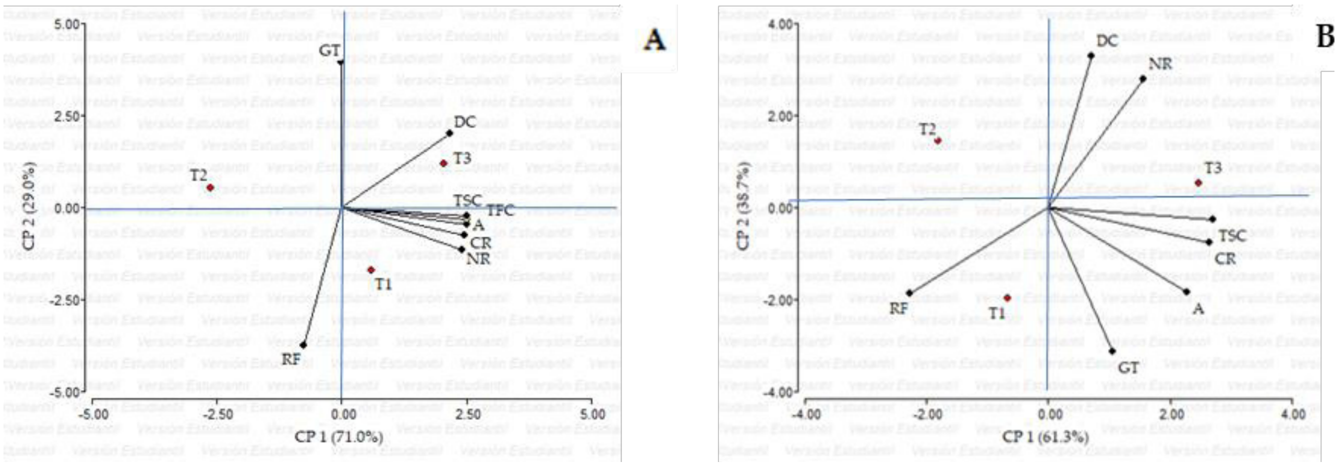

Figure 5. Principal component analysis (biplot graph) of morphological and productive variables by effect of spatial arrangements in *Jatropha curcas* L. in the second year of evaluation. A: low rainfall period (PPLL); B: rainy period (PLL). T1: Jc monoculture; T2: 50 % Jc + 50 % food crop; T3: Jc intercropped with food crop; A: height; DC: crown diameter; GT: stem thickness; NR: number of branches; CR: number of clusters; TFC: total fruits harvested; TSC: total seeds harvested; RF: fruit yield.

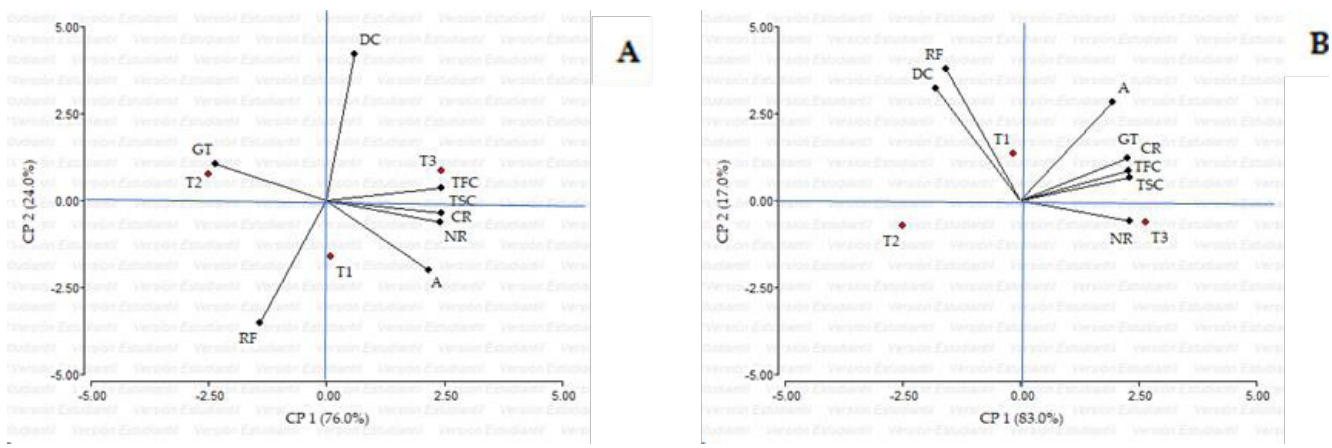

Figure 6. Principal component analysis (biplot graph) of morphological and productive variables by effect of spatial arrangements in *Jatropha curcas* L. in the third year of evaluation. A: low rainfall period (PPLL); B: rainy period (PLL). T1: Jc monoculture; T2: 50 % Jc + 50 % food crop; T3: Jc intercropped with food crop; A: height; DC: crown diameter; GT: stem thickness; NR: number of branches; CR: number of clusters; TFC: total fruits harvested; TSC: total seeds harvested; RF: fruit yield.

variables. The highest yields were achieved when using 50 % *J. curcas* and 50 % food crop (T2). However, for the former, they were higher with the spatial arrangement in which *J. curcas* was intercropped with food crops (T3). In CP2, 24 % of the variability was extracted; this component is explained by DC, and in the opposite direction, RF, for which the highest values were reached when using *J. curcas* in monoculture (T1). For the biplot corresponding to the PLL of the third year of evaluation (Figure 6B), the accumulated variance at that time was 100 %, which was explained by the first and second components, 83 and 17 %, respectively. In CP1, A, GT, NR, CR, TFC, and TSC contributed, which were positively related. Within this component, but with a negative relationship, there was DC. Furthermore, when using the spatial arrangement in which *J. curcas* was intercropped with food crops (T3), the highest values for A, GT, NR, CR, TFC, and TSC were reached. For CP2, RF was the variable with the greatest weight in the formation of this axis, for which the highest values were obtained with the tree control treatment (T1).

The results of the spatial arrangements effect on fruit yield (Figure 7) show that the values of this variable were higher when *J. curcas* was planted in monoculture (T1), with yields approaching or exceeding 2 Mg ha^{-1} at each harvest.

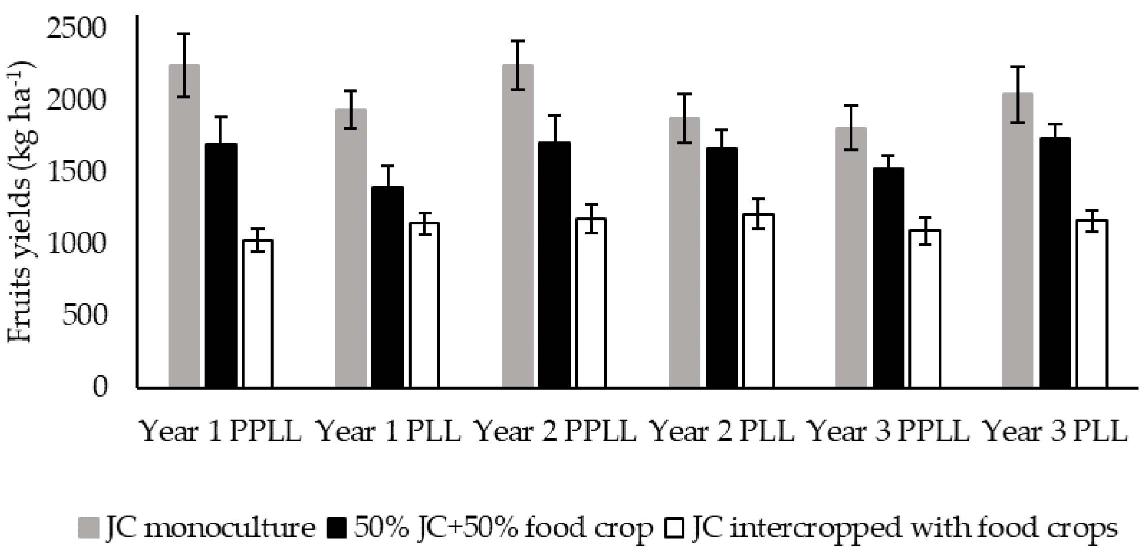

Figure 7. Effect of spatial arrangements on fruit yield of *Jatropha curcas* L. during two climatic periods in three crop years. Vertical lines indicate confidence intervals for each treatment. Results are not shown for T4 because it presents only food crops in rotation. PLL: rainy period; PPLL: low rainfall period.

The yield of the association of 50 % *J. curcas* and 50 % food crop (T2) was higher than that obtained with *Jatropha* intercropped (T3) and similar to T1 in the rainy period of the second year. Similarly, with T3 the most stable yields were obtained, since no differences were observed between the years evaluated.

Regarding the yields of food crops associated with *J. curcas* (Jc) during the experimental period, the results of each of the spatial arrangements in combination with Jc (T2 and

T3) and food crops in monoculture (T4) are reported (Table 2). For beans sown in two years (2016 and 2018), no differences were found between the spatial arrangements of 50 % Jc and 50 % bean (T2) and Jc intercropped with food crop (T3) relative to monoculture (T4). For T2, yields were slightly lower than the national average, which is 0.89 Mg ha^{-1} (ONEI, 2021).

Table 2. Effect of different spatial arrangements on the yield of food crops associated with *Jatropha curcas* L. during the experimental period.

Treatments*	Yield (Mg ha^{-1})				
	Beans		Sweet potato		Squash
	2016	2018	2017	2019	2018
T2	0.86	0.78	6.85	7.25	6.59
T3	0.91	0.84	8.25	8.37	11.89
T4	0.94	0.93	10.17	9.15	13.83
IC (±)	0.14	0.08	0.85	1.04	1.13

T2: 50 % Jc + 50 % food crop; T3: Jc intercropped with food crop; T4: monoculture of food crop; iC (±): confidence interval (95 %). *The results of treatment 1 are not shown since *Jatropha* was grown in monoculture.

Regarding the sweet potato crop, in 2017, differences were found among all the evaluated treatments. With the control (T4), the highest yield (10.17 Mg ha^{-1}) was obtained, being higher than the national average for the country (9.3 Mg ha^{-1}) (ONEI, 2021). However, in 2019, there were no differences between monoculture (T4) and when using *J. curcas* intercropped with the food crop (T3). For squash, the highest yields were obtained with monoculture (T4) and with *J. curcas* intercropped with food crop (T3), which did not differ between them but did when compared to T2 (50 % Jc + 50 % food crop), which had lower yields and was below the national average, which is close to 10 Mg ha^{-1} (ONEI, 2021).

The biological efficiency of the polycultures was positive given that the equivalent land use (UET) was higher in monoculture with respect to all the associations (Table 3). However, the highest values were obtained with the T2 spatial arrangement for most crops, except for squash, which was 1.35 in T2 and 1.50 in T3.

The productive variables number of clusters (CR), total fruit (TFC), and seeds harvested (TSC) had a positive correlation within the first principal component in each period, which indicated the high degree of complementarity existing in these productive traits. In addition, with the largest furrow spacing in an intercropping arrangement (T3), there were high values for each of these variables. This indicates that these association systems were effective over time.

Table 3. Equivalent Land Use (UET) behavior according to spatial arrangement variants.

Treatments*	UET				
	Beans		Sweet potato		Squash
	2016	2019	2017	2019	2018
T2	1.66	1.68	1.39	1.63	1.35
T3	1.43	1.50	1.40	1.47	1.50

T2: 50 % Jc + 50 % food crop; T3: Jc intercropped with food crop. *Treatments 1 and 4 are not presented because they were used as controls in the absence of intercropping in these spatial arrangements.

The shorter planting distance used in the *J. curcas* monoculture (T1) and T2 (50 % Jc + 50 % food crop) had the lowest CR, which could be associated with the reduced space between *J. curcas* plants and, therefore, a lower incidence of radiation, which can decrease photosynthetic activity and affect the productive stage. Meanwhile, the opposite occurred in the more open arrangements (Agustí, 2013). On the other hand, the variability in fruit yield (RF) was explained by CP2, and the highest values were obtained when *J. curcas* was used in monoculture (T1), which could be due to the high density of plants per hectare in this treatment. Therefore, it could be corroborated that the highest RF was followed by T2 (Figure 7), which responds to the same planting distance and plant density, compared to T1. The lowest height values (A) were obtained with treatments T1 and T2, so it was considered that a high plant density increases competition to assimilate necessary resources, which could be limited and influence growth from the first year of study (Rehling *et al*., 2021).

For crown diameter (DC), stem thickness (GT), and number of branches (NR), it was detected that these morphological characters were highly variable, as they were indistinctly represented in the two components in a positive or negative way, which could be determined by the genetic heterogeneity of the species (Rincón-Rabanales *et al*., 2016). The higher DC values with T3 during the first and second years of evaluation indicate that plants were able to reach their maximum vegetative development given a larger space between furrows (5 x 2 m), an aspect that varied once they reached full physiological maturity (Alegría-Muñoz, 2016).

The highest NR values were detected with T3. It is presumed that due to the more open spaces given by the greater separation between the arboreal furrows, the plants were able to develop a projected growth pattern in lateral branching. However, for GT, there was no clear trend for any treatment since, in each period, the behavior varied. In this sense, Agustí (2013) stated that the dilation or contraction of stem thickness is considered an important indicator of plant water status.

Considering these criteria, it was possible to infer that the tree was able to supply the water needs with the rainfall for each period, given the response expressed from the first year to the end of the evaluation period, since the thickness values did not fluctuate. These aspects corroborate that *J. curcas* reached maximum morphoproductive development when the rainfall range oscillated between 300 and 1800 mm (Kremer *et al.*, 2020), which corresponds to the accumulated rainfall for each year of the experimental stage. On the other hand, yields of beans, sweet potato and squash were considered low when compared to the national average for the country (ONEI, 2021). For squash, yields were less favorable due to the rainfall in 2018, which had accumulated 1688.6 mm, which was higher than the historical average of 1338.8 mm.

It is inferred that the lower yields for T2 may be associated with the spatial arrangement of the squash plants, which were unprotected and therefore the intense rains caused severe damage, while with T3, the associated plants were between the furrows of *J. curcas* that provided them with protection. Although high yields were not achieved in the food crops, it is considered that the association of crops is favored by the diversity of species and benefits provided by these plants. This evidence is corroborated by the positive equivalent land use (UET) value obtained for T2 and T3. Therefore, the use of associated crops was considered feasible, mainly in the arrangement of 50 % Jc + 50 % food crop (T2), which was superior to *J. curcas* intercropped with food crop (T3).

Not all species associated with *J. curcas* constitute viable systems, as it will depend on other factors characteristic of each food crop, such as growth habits, branching patterns, nutrient demands, and cultural requirements (Khanal *et al*., 2021). Therefore, it is important to determine the "ideal" spatial arrangements between different plant species in which responses can be obtained among the best associations, as well as to test with different organic fertilizers and investigate aspects of subsoil cover and planting distances (Valdés-Rodríguez *et al*., 2013; Valdés-Rodríguez *et al*., 2020), since the main objective is to achieve sustainability of agroecosystems and food security through agricultural biodiversity.

CONCLUSIONS

With the spatial arrangement of 50 % *Jatropha curcas* L. and 50 % food crops, the highest production of the tree was achieved. However, in the morphological variables, no clear trend in favor of any treatment or its relationship with yield was detected. The biological efficiencies (given by diversification and better land use) from the different associations of the *Jatropha* plant and associated crops were also positive.

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