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Aerial morphometry in *Moringa oleifera* Lam. at different planting densities, in savannahs of Monagas, Venezuela

Morfometría aérea en *Moringa oleifera* Lam. a diferentes densidades de siembra, en sabanas de Monagas, Venezuela

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Abstract

In order to evaluate the primary morphometric variables, of branches and leaves per plant, in moringa, an experiment was set up at the "Guachimarí" farm, Maturín municipality, Monagas state, Venezuela. A nursery was created to produce seedlings, which were later transplanted to the field. A randomized block design was used, with five treatments or planting densities (16,000; 20,000; 26,666; 40,000 and 80,000 plants.ha^{-1}), four repetitions and experimental units of 9 m^2. The harvest was carried out 215 days after transplantation. Prior to this, the primary aerial morphometry was determined: plant height (PH), basal stem diameter, number of branches and the robustness index (RI); after this, the branch morphometric variables were quantified: length, diameter, number of leaves and height to the first branch (HFB); and in the leaf: length and width. The values were studied using the ANOVA procedure, descriptive statistics, regression analysis and correlations. Planting density did not affect (P>0.05) most of the foliage morphometric variables, except for RI and HFB, with coinciding maxima, close to the critical density of 50,000 plants·ha^{-1}, and influenced by physical limitations of the soil. In morphometric correlations, the variable PH was positively associated with variables measured in branch and leaf (r= 0.71**); in contrast, there was a negative association between the number of branches·plant^{-1} and the number of leaves·branch^{-1} (r= -0.74**). Genetic and physiological aspects of the crop are involved, especially the habit of vertical growth at high rates.

Keywords: *Moringa oleifera*, planting density, robustness index, morphometric correlation.

Resumen

Con el objetivo de evaluar las variables morfométricas primarias, de ramas y de hojas por planta, en moringa, se instaló un experimento en el fundo "Guachimarí", municipio Maturín, estado Monagas, Venezuela. Se realizó un vivero para producir plántulas, que fueron posteriormente trasplantadas a campo. Se empleó el diseño de bloques al azar, con cinco tratamientos o densidades de siembra (16.000, 20.000, 26.666, 40.000 y 80.000 plantas·ha^{-1}), cuatro repeticiones y unidades experimentales de 9 m^2. La cosecha fue realizada 215 días después del trasplante, previo a la misma se determinó la morfometría aérea primaria: altura de planta (AP), diámetro basal del tallo, número de ramas y el índice de robustez (IR); posterior a esta, se cuantificaron las variables morfométricas de rama: longitud, diámetro, número de hojas y altura a la primera rama (APR); y en la hoja: longitud y ancho. Los valores fueron estudiados mediante procedimiento ANAVA, estadística descriptiva, análisis de regresión y correlaciones. La densidad de siembra no afectó (P>0,05) la mayoría de las variables morfométricas del follaje, a excepción del IR y la APR, con máximos coincidentes, cercanos a la densidad crítica de 50.000 plantas·ha^{-1}, e influenciados por limitaciones físicas del suelo. En correlaciones morfométricas, la variable AP se asoció positivamente con variables medidas en rama y en hoja (r= 0,71**); en contraste hubo asociación negativa entre el número de ramas·planta^{-1} y el número de hojas·rama^{-1} (r= -0,74**). Aspectos genéticos y fisiológicos del cultivo están involucrados, sobretodo el hábito de crecimiento vertical a tasas elevadas.

Palabras clave: *Moringa oleifera*, densidad de siembra, índice de robustez, correlación morfométrica.

Introduction

Moringa oleifera Lam. is a multi-purpose plant of Asian origin that tolerates long periods of drought and adapts to a wide range of edaphoclimatic conditions (Carrión et al., 2022). Its foliage is recognized as an excellent nutritional supplement for both humans and animals, due to its antioxidant, insulin-sensitizing, and immune-modulating properties. It is also attributed with anti-cancer, anti-inflammatory, antimicrobial, antifungal, antiviral, and anthelmintic activities(Hernández and Iglesias, 2022).

Likewise, it can be readily propagated by sexual reproduction, as its seeds lack a dormancy period and can remain viable for up to one year. *Moringa* cultivation is internationally recognized for its use in ruminant feeding, showing significant improvements in productive variables (Sánchez-Santillán et al., 2022). Korsor et al. (2019) reported that the species can achieve dry biomass yields exceeding 15 $t·ha^{-1}·year^{-1}$ (approximately 1.87 $t·ha^{-1}$ per cutting), influenced in part by planting density. Motis and Reader (2019) observed dry biomass yields ranging from 0.12 to 0.25 $t·ha^{-1}$ in plantations with mixed fertilization programs and low planting densities of 2,285.71 $plants·ha^{-1}$ (spacing of 1.25 m × 3.5 m)

Lago-Abascal et al. (2024) considered a planting density of 41,666.66 $plants·ha^{-1}$ (spacing of 0.80 m × 0.30 m) as optimal for producing high-quality forage under favorable soil and rainfall conditions. Higher densities led to plant competition for light (phototropism). Similarly, Sosa-Rodríguez et al. (2017) established the crop at different planting densities and reported that shorter planting distances resulted in increased total plant height and higher biomass yields, although the number of shoots was significantly lower. Additionally, Navas-Panadero (2019) noted that climatic conditions influenced yield and the stem-to-leaf ratio of the plant.

Currently, producers and technicians recognize the nutritional benefits of *Moringa*, but lack knowledge regarding its cultivation management to achieve satisfactory results in foliage production. The main weakness lies in the establishment of forage banks. Therefore, the objective of the present research was to evaluate key morphometric variables, including: plant height, basal stem diameter, number of branches, and plant robustness index. In addition, the following branch characteristics were analyzed: length, diameter, number of leaves, and height of the first branch, as well as leaf length and width, in order to determine the appropriate planting density.

Materials and methods

Location of the experiment

The experiment was conducted at the "Guachimarí" farm, located in Primero de Mayo, San Vicente parish, Maturín municipality, Monagas state, Venezuela, geographically located at 9°43'00.3" N and 63°17'55.1" W, at an altitude of 116 meters. The experimental area is situated in the tropical dry forest agroecological zone, with Ultisol-type soils and savanna vegetation. The annual rainfall is 1,069 mm, and the average temperature is 25.8 °C (Climate.data.org, 2023).

Setting the nursery

A nursery was established to produce moringa seedlings. Mature fruits of the species *M. oleifera* var. *supergenius* were harvested from the seed bank located at Agrobase "Indio Maturín", in the Las Cayenas sector, Santa Cruz parish, Maturín municipality, Monagas state. Prior to sowing, seeds were selected based on size (approximate equatorial diameter between 10 and 13 mm) and color (dark brown seed coat with whitish wings) (Romero-Marcano et al., 2022). Seeds were disinfected with a 10% v/v sodium hypochlorite solution, followed by three rinses in running water. They then underwent a pre-germination treatment by soaking in running water for 12 hours prior to sowing.

Sowing was carried out in 2 kg black polyethylene bags, filled with a substrate composed of 80% sandy loam soil and 20% cattle manure. The physical and chemical characterization of the substrate was conducted at the Soil Laboratory of Universidad de Oriente, Juanico Campus, and revealed the following properties: pH 5.81, electrical conductivity 18.16 $dS·m^{-1}$, cation exchange capacity 3 $meq·100\ g^{-1}$, organic matter content 3.87%, and phosphorus content 14 ppm.

Three seeds were placed per bag, at a depth of 2 cm. Immediately afterward, the substrate was saturated with water, and from that point on, irrigation was applied every other day. Once the seedlings emerged, thinning was performed using scissors, keeping the most vigorous seedling in each bag. The nursery phase lasted 42 days.

Prior to field establishment, a simple random sampling was conducted with a sample size (n) of 85 seedlings (from a total nursery population N= 1,000 seedlings). The following variables were measured: seedling height, stem diameter, and number of leaves, with average values of 49.69 ± 0.99 cm, 8.71 ± 0.12 mm, and 13.13 ± 0.13, respectively. This was done to characterize the material to be transplanted to the field.

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Setting the experiment in the field

The effective trial area covered 506 m², including the borders of the experimental area, with dimensions of 23 m in length and 22 m in width. The experiment consisted of 20 plots, organized into four strips, separated by 2 meters. Each strip contained five plots, and each plot measured 9 m² with dimensions of 3 × 3 meters.

The planting densities evaluated were: 16,000, 20,000, 26,666, 40,000, and 80,000 plants·ha^{-1}, with row spacing of 125, 100, 75, 50, and 25 cm, respectively, while the intra-row spacing remained constant at 50 cm. Each planting density was represented in four independent plots, one per strip.

Prior to planting, manual land preparation was carried out, including weeding and marking the plots, which were oriented perpendicularly to the slope. Once the plots were defined, planting holes 20 cm deep were opened using a motorized auger (EFCO®, model TR 1551, Italy). After field planting, standard agronomic management was applied, including: plot weeding every 30 days; leafcutter ant (*Atta* sp.) control using Attilan®, applying 5 g at the colony entrance; and control of other foliage pests with CYPER® spray at a concentration of 1 mL·L^{-1}.

The trial area was equipped with a sprinkler irrigation system. A total of 4.5 months elapsed from field establishment to uniformity pruning.

Physisco-chemical analysis of the soil in the experimental area. Pre adn psot-harvest tests

Prior to planting, the soil in the experimental area was physically and chemically characterized. Using samples taken at a depth of 20 cm, the soil was determined to be of sandy loam texture, with a pH of 5.16, electrical conductivity of 1.65 dS·m^{-1}, organic matter content of 2.33%, cation exchange capacity of 1.8 meq·100 g^{-1}, and phosphorus content of 2.54 ppm.

After planting the crop in the field, a soil pit was dug adjacent to the experimental plots, to a depth of 120 cm, and the different soil horizons were characterized. Bulk density, determined using the Uhland method, was: 1.6036 g·cm^{-3} (0-10 cm), 1.7267 g·cm^{-3} (10-20 cm), 1.6171 g·cm^{-3} (20-30 cm), and 1.6863 g·cm^{-3} (30-40 cm). Soil moisture content was: 5.25% (0-10 cm) and 5.46% (20-30 cm). Infiltration rate was measured at 0.034 L·h^{-1} (0-10 cm), 0.144 L·h^{-1} (10-20 cm), 0.408 L·h^{-1} (20-30 cm), and 0.756 L·h^{-1} (30-40 cm).

According to Silva-Araujo and Mirás-Avalos (2024), based on these characteristics, the soil in the experimental area presented compacted or moderately compacted surface horizons.

Uniformity prunning and harvest

Uniformity pruning was carried out at a height of 40 cm from the base of the plant, using hand saws and pruning shears. Following the uniformity cut, nitrogen fertilization was applied by adding 10 g of urea per plant. The harvest took place 90 days after the uniformity cut.

Air morphometric determination

After 90 days from the uniformity cut, and prior to harvest, the primary aerial morphometric traits were measured: plant height, basal stem diameter, number of branches, and the plant robustness index. Once the harvest was completed, the following branch morphometric variables were recorded: length, diameter, number of leaves, and height of the first branch. For the leaves, length and width were measured.

Procedure for meeasuring primary morphometrics

For each plant, height was measured using a flexible measuring tape, from the base of the plant to the apical bud. Basal stem diameter was measured 5 cm above the ground using a MITUTOYO® digital caliper, model CD-6"CS. The number of branches per plant was recorded through visual counting, and the robustness index was calculated as the ratio between plant height (cm) and basal stem diameter (mm) (Rodríguez-Ortiz et al., 2021).

Procedure for measuring branch morphometrics

For each plant, the branch length was measured from the base of the regrowth to the apical bud. The branch diameter was measured at the base of the regrowth using a MITUTOYO® digital caliper, model CD-6"CS. The number of leaves per branch was quantified through visual counting, and the height of the first branch was measured from the base of the plant to the first regrowth, using a flexible measuring tape.

Procedure for measuring leaves morphometrics

For the pair of basal leaves on each branch, leaf length was measured from the base of the petiole to the apex, while the maximum width was measured perpendicular to the leaf rachis.

Experimental design and data analysis

A randomized block design was implemented with five treatments, differentiated by the five planting densities (plants·ha^{-1}). The treatments were: 16,000 (D1); 20,000 (D2); 26,666 (D3); 40,000 (D4); and 80,000 (D5), with four replications or blocks, corresponding to the four planting strips, for a total of 20 experimental units (EU). Each EU consisted of a 9 m² plot.

The data obtained for the morphometric variables and the robustness index were initially analyzed using the Shapiro-Wilk and Bartlett tests, to verify the assumptions of normality of errors and homogeneity of variances, respectively.

Treatment comparisons were performed using ANOVA procedures. Variables that were not statistically significant were analyzed using descriptive statistics, based on the calculation of means and standard errors, both overall and by response category. Variables with significant differences were interpreted using simple regression models, considering planting density as the independent variable (X).

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Pearson correlation analysis was applied among the different aerial morphometric variables. Variables with significant correlation coefficients were represented using scatter plots. All statistical procedures were carried out using InfoStat software, version 2020 (Di Rienzo et al., 2020).

Results and discussion

Primary aerial morphometry

Table 1 shows the average values of primary aerial morphometric traits in *Moringa*, according to planting density. The statistical analysis did not detect significant differences (P>0.05) in most of the primary aerial morphometric variables: plant height, basal stem diameter, and number of branches. However, for the robustness index, a significant difference was found (P≤0.05).

For plant height, recorded values ranged from 39.16 ± 6.99 cm to 53.46 ± 1.93 cm; for basal stem diameter, values ranged from 14.43 ± 0.67 mm to 14.92 ± 0.59 mm. The number of branches per plant varied between 2.50 ± 0.20 and 3.17 ± 0.33.

The plant height values obtained in this study were lower than those reported by Barrios-Gómez et al. (2022), who recorded 86.1 cm with higher planting densities than those used in the present experiment. Those authors also reported greater stem diameters and more branches, at 17.55 mm and 4.7 branches per plant, respectively. In contrast, Ruíz-Hernández et al. (2021) reported similar values for number of branches, with an average of 2.64 branches per plant in plantations with lower planting densities (1,111.11 plants·ha⁻¹).

Table 1. Corm aerial morphometry, grown at different densities.

Density (plantas·ha⁻¹)	Aerial morphometry (X̄±EE)			
	Plant height (cm)	Basal diameter (mm)	Number of branch	Robustness index
16,000	39.16±6.99	14.77±1.44	2.50±0.20	2.64±0.36
20,000	45.70±3.93	14.43±0.67	2.53±0.38	3.17±0.24
26,666	44.68±1.80	14.92±0.59	3.81±0.83	2.99±0.04
40,000	53.46±1.93	14.71±0.58	2.93±0.54	3.64±0.13
80,000	51.02±2.40	14.72±0.14	3.17±0.33	3.47±0.18
P vaue	0.9835	0.9835	0.3424	0.0437
Average	46.80**±3.41**	14.71**±0.68**	2.98±0.45	

The values obtained may have been influenced by soil compaction effects, as root system development is directly related to the aerial growth of the plant. When roots are small and unable to extract sufficient water and nutrients, smaller plants are formed (Cabeza and Claassen, 2017).

Figure 1 shows the trend observed in the regression with a quadratic fit (R^2= 0.81), displaying a rising convex curve, with an increase in the robustness index from a planting density of 16,000 plants·ha⁻¹ up to 56,833 plants·ha⁻¹ (maximum point Y= 3.72), followed by a subsequent decline in the index.

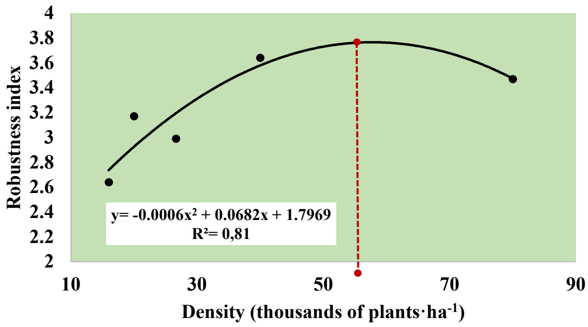

Figure 1. Robustness index relative to moringa planting denisity. The red dotted line representes the highest point in the robustness index.

The initial increase in the robustness index at lower planting densities was interpreted as greater height growth relative to basal stem diameter in the *Moringa* plant. In contrast, the decline in the index at higher planting densities was understood as greater basal stem diameter growth relative to plant height. This behavior can be related to the limiting physical conditions of the soil, as in lower planting densities, the soil tillage was less intensive (due to more widely spaced holes), which indirectly implies greater compaction in the plots.

On the other hand, in higher planting densities, with closer hole spacing, there was greater soil disturbance and thus less compaction due to the tillage effect. This condition reduced plant stress; consequently, Romero-Marcano et al. (2021) reported greater stem diameter growth in moringa compared to height, when substrate porosity and/or fertility improved, associated with greater crop comfort. Similarly, Alvarado-Ramírez et al. (2020) also obtained descending regression trends for aerial growth (height), with a maximum point near 50,000 plants·ha⁻¹.

Based on the quantified primary morphometry, no direct effect of light competition among densities was observed. Instead, soil conditions stood out as the main limiting factor for proportional aerial growth (height:diameter ratio). This was also due to the moringa crop's tendency to maintain indeterminate orthotropic

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growth, regardless of environmental conditions (Alonso Lazo et al., 2021).

Branch morphometry

Table 2 presents the average values of branch morphometric traits: branch length, basal branch diameter, number of leaves, and height of the first branch, according to the planting density used. The statistical analysis did not detect significant differences in branch length, basal branch diameter, or number of leaves per branch; however, the height of the first branch showed significant differences (P≤0.05).

Branch length ranged from 6.65 ± 1.80 cm to 10.30 ± 2.06 cm; basal branch diameter values ranged between 3.45 ± 0.43 mm and 4.14 ± 0.41 mm; and the number of leaves per branch varied from 5.03 ± 0.94 to 6.05 ± 0.63. These results were lower than those reported by Ledea-Rodríguez et al. (2018), who, at a planting density of 80,000 plants·ha^{-1} and a 60-day cutting frequency, recorded basal branch diameters of 11 mm and 11 leaves per branch, respectively.

Table 2. Morphometry of moringa branches sown at different densities.

Density (plantas·ha^{-1})	Branch morphometry (X̄±EE)			
	Branch lenght (cm)	Branch base diameter (mm)	Number of leaves per branch	Height of first brancha (cm)
16,000	6.65±1.80	4.08±0.76	5.67±0.48	19.56±5.43
20,000	7.72±0.89	3.45±0.43	5.48±0.49	27.09±3.21
26,666	6.72±1.33	3.92±0.97	5.03±0.94	25.14±2.25
40,000	10.30±2.06	4.14±0.41	6.05±0.63	33.05±1.25
80,000	9.94±1.66	4.03±0.41	5.44±0.30	29.53±2.41
P value	0.4490	0.9413	0.8203	0.0120
Average	8.26±1.54	3.92±0.59	5.53±0.56	

Figure 2 shows the trend observed in the regression with a quadratic fit (R^2= 0.81), exhibiting a rising convex curve, with an increase in the height of the first branch from a planting density of 16,000 plants·ha^{-1} up to 55,610 plants·ha^{-1} (maximum point Y= 34.62 cm), followed by a subsequent decline.

The increase in the height of the first branch with higher planting densities could be interpreted as a physiological response of the plant to light and space competition within the plot. As the crop population increased, light and space availability per plant decreased, which may have caused regrowth to appear higher up on the stem (Lago-Abascal et al., 2024). However, if that were the case, the expected regression model would be linear, and the highest densities would show a continuous increase in this variable—which was not observed. Instead, the initial rise in the curve appears to be associated with the height and diameter trends reflected in the robustness index, where plants with proportionally greater height growth tended to position regrowth

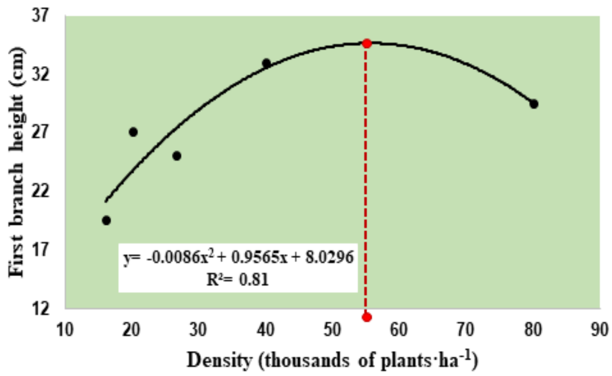

Figure 2. First branch height (cm) relative to moringa planting densityde acuerdo con la densidad del cultivo de moringa. The red dotted line represents the highest value (cm).

The decrease in the height of the first branch in the higher-density plots may be attributed to a compensatory effect resulting from better root development in plants growing in a less compacted substrate, which allowed for greater foliage formation, making the plants less sensitive to the assumed light and space competition (Alonso et al., 2021; Romero-Marcano et al., 2021).

Leaf morphometry

Table 3 presents the values for leaf morphometric traits: leaf length and maximum leaf width, according to the planting densities studied. Statistical analysis did not detect significant differences in any of the leaf morphometric variables. Leaf length ranged from 9.25 ± 2.61 cm to 11.65 ± 0.88 cm, while the maximum leaf width ranged from 5.23 ± 1.46 cm to 8.25 ± 0.53 cm.

Alvarado-Ramírez et al. (2020) reported leaf lengths of 4.44, 20.43, and 19.49 cm in an experimental moringa plantation with planting densities of 50,000, 100,000, and 200,000 plants·ha^{-1}, respectively, under cutting intervals of 28 days. A direct comparison indicated that all leaf lengths obtained in this study exceeded the value reported for the 50,000 plants·ha^{-1} density, likely due to the longer cutting interval (90 days) used in the present study.

In general, the lack of significant differences in the aerial growth variables of *Moringa* cultivation was a consistent experimental pattern. Authors such as Barrios-Gómez et al. (2022) and Ledea-Rodríguez et al. (2018) observed the same behavior under field conditions, which was mainly attributed to the rapid growth rate of *M. oleifera*—a genetic trait that manifests regardless of environmental conditions (Alonso et al., 2021).

Table 3. Moringa leaf morphompetry sown at different densities.

Density	leaf morphometry in cm (X̄±EE)	
(plants·ha-1)	Leaf length	Highest leaf width
16,000	9.25±2.61	5.23±1.46
20,000	9.94±0.23	7.12±0.45
26,666	8.97±1.51	6.90±1.97
40,000	11.65±0.88	8.25±0.53
80,000	11.31±1.25	7.68±1.40
P value	0.5764	0.4977
Average	10.22±1.29	7.03±1.16

In general, the lack of significant differences in the aerial growth variables of moringa cultivation was a consistent experimental outcome. Authors such as Barrios-Gómez et al. (2022) and Ledea-Rodríguez et al. (2018) confirmed this same behavior under field conditions, which was mainly attributed to the rapid growth rate of *M. oleifera*—a genetic characteristic that was expressed regardless of environmental conditions (Alonso et al., 2021).

Morphometric correlations

The statistical association analysis among the morphometric variables detected significant and highly significant correlations in 10 combinations, involving the variables: plant height, height of the first branch, number of branches per plant, number of leaves per branch, branch diameter, branch length, leaf length, and maximum leaf width, as described in detail below.

Correlation between plant height vs. height of the first branch and leaf length. The variable plant height showed positive, highly significant correlations with both height of the first regrowth and leaf length (0.83 and 0.74, respectively), indicating that as plant height increased, so did the height of the first branch and leaf length (figure 3).

Since *Moringa* plants prioritize vertical elongation, with growth rates of approximately 23 mm·day^{-1} (Valdés-Rodríguez et al., 2018), stem elongation caused lower shoot formations to appear higher on the stem. Apparently, this elongation stimulus may also extend to leaf length growth.

This associative behavior between plant height and leaf-related measurements was also observed in a study conducted by Elizondo-Cabalceta and Monge-Pérez (2019), who reported a positive and highly significant correlation between plant height and leaf area (r= 0.90), in mature solanaceous plants. Similarly, Barrios-Gómez et al. (2022) reported positive and highly significant correlations between total aerial biomass yield and both plant height and total leaf yield, in high-density *Moringa* plantations.

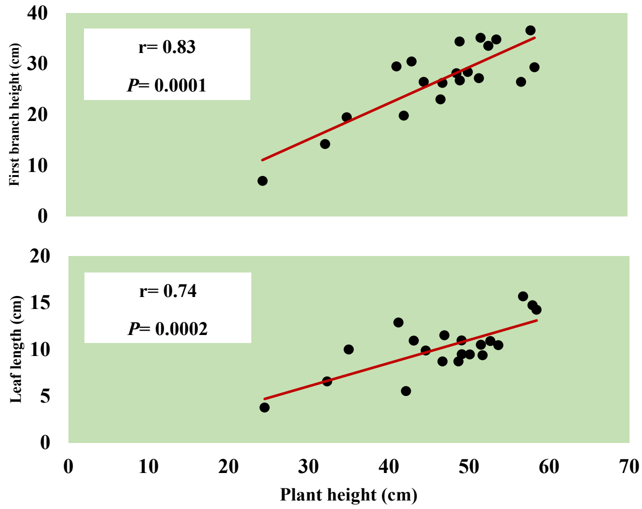

Figure 3. Correlations between morphometric variables: plant height (X axis) vs first plant height in cm (b).

The analysis of the association between number of branches per plant vs. number of leaves per branch revealed a highly significant negative correlation with number of leaves per branch (r= -0.74, figure 4). This indicates that as the number of branches per plant increased, the number of leaves per branch decreased. This statistical relationship could be interpreted as a genetically driven compensatory response, whereby the plant regulates its photosynthetically active leaf area under varying planting densities.

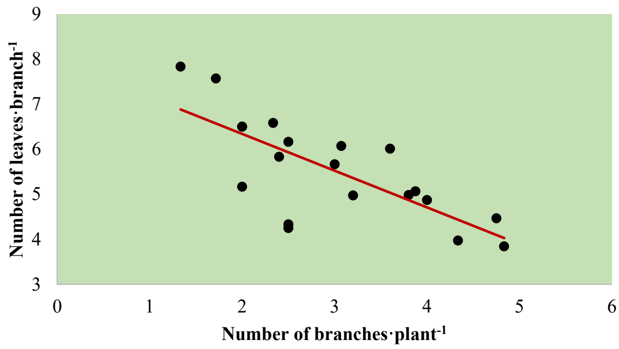

Figure 4. Correlations between morphometric variables: number of branches.plant^{-1} vs number of leaves.branch^{-1}.

Relationship between the degree of association between branch diameter and branch length, number of leaves per branch, leaf length, and leaf width. The variable branch diameter showed positive, highly significant correlations with branch length, number of leaves per branch, leaf length, and leaf width (0.75, 0.71, 0.77, and 0.75, respectively), indicating that as branch diameter increased, so did the branch length, the number of leaves per branch, and both the length and width of the leaf (figure 5). From a statistical standpoint, this plant behavior reflects a close and accelerated physiological relationship in *Moringa* between the formation of photoactive tissues and the development of semi-woody structures in the shrub. The thickening of stems and branches corresponds with the foliar canopy expansion, as also argued by Garate-Quispe et al. (2022) in similar positive correlations reported for forest species.

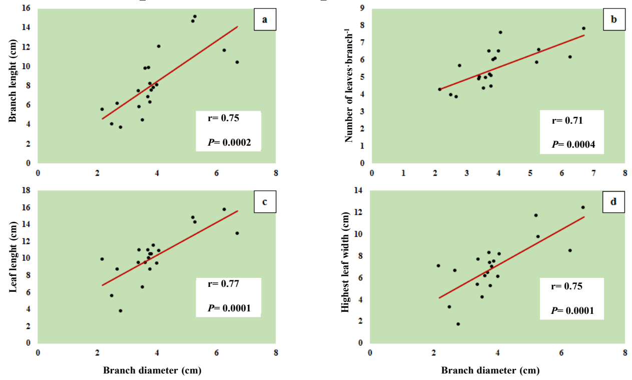

Figure 5. Correlations between morphometric variables: branch diameter in cm (X axis) and branch lenght in cm (a); number of leaves·branch^{-1} (b); leaf lenght in cm (c) and highest leaf width in cm (d)

Relationship between branch length and leaf length and maximum leaf width. The variable branch length showed positive, highly significant correlations with both leaf length and maximum leaf width (0.83 and 0.80, respectively); it was evident that as branch length increased, so did the leaf length and maximum leaf width (figure 6).

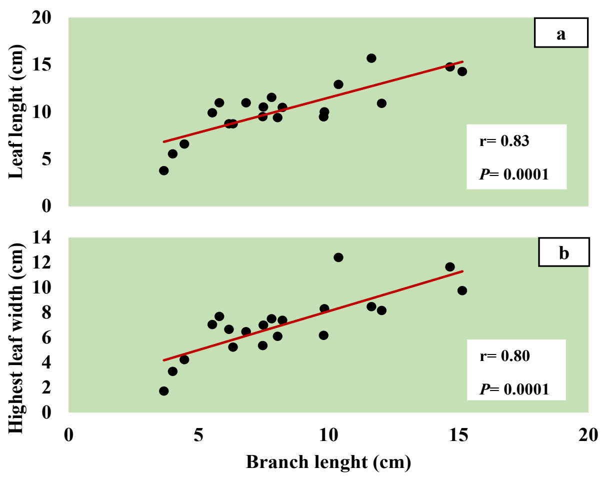

Figure 6. Correlations between morphometric variables: branch lenght in cm in cm (X axis) vs leaf lenght in cm (a) highest leaf width in cm (b).

This biological pattern reflected the phenological condition of the crop, where branch dimensions were clearly linked to leaf dimensions. Considering that *Moringa* foliage contains high levels of zeatin (a member of the cytokinin family), the growth of branches and leaves can be continuously stimulated by these plant growth regulators, as stated by Ortiz-Rojas et al. (2017)

The correlation analysis between leaf length and maximum leaf width indicated that leaf length had a positive, highly significant value with respect to maximum leaf width (r= 0.88, figure 7). These findings suggest that as leaf length increased, maximum width also increased proportionally.

This may represent a proportional relationship genetically and physiologically regulated in *Moringa* under the planting density management conditions used in the study. As *Moringa* leaves are rich in cytokinins, this plant growth regulator is known to promote cell division and tissue morphogenesis, contribute to resistance against abiotic and biotic stress, aid in in vitro plant propagation, and support increased crop yield (Borjas-Ventura et al., 2020).

A similar pattern between leaf length and maximum width was observed by Del Castillo-Batista et al. (2017), who reported a significant positive correlation (r= 0.77) between these morphometric variables in plants of the genus *Cestrum* (Family: Solanaceae).

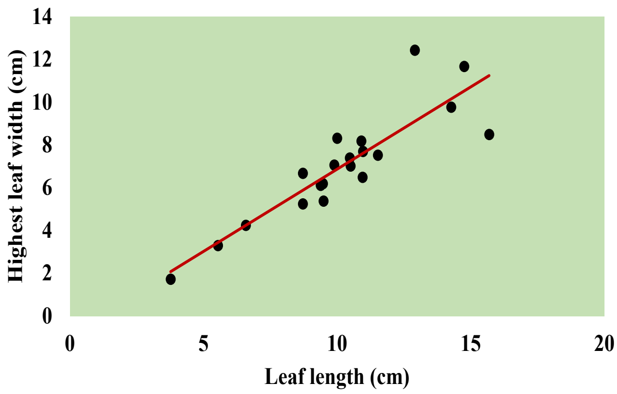

Figure 7. Positive correlations between variables: leaf length in en cm and highest leaf width in cm.

A similar relationship between leaf length and maximum width was observed by Del Castillo-Batista et al. (2017), who reported a significant positive correlation (r= 0.77) between these morphometric variables in plants of the genus *Cestrum* (Family: Solanaceae).

The findings observed under the experimental conditions of the tropical dry forest indicated that the absence of significant differences in primary aerial, branch, and leaf morphometric variables suggested that these values were not influenced by the planting densities evaluated. However, the robustness index and the height of the first branch provided valid criteria for selecting a more favorable planting density.

The morphometric correlations studied revealed the degree of association among the measured variables and described, in most cases, a proportional growth of foliage in relation to plant

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height. Additionally, an inverse (compensatory) relationship was confirmed between the number of branches per plant and the number of leaves per branch, which may explain the uniformity of foliage under varying comparison condition.

Conclusion

Planting density did not affect most of the aerial morphometric variables of moringa, except for the robustness index and the height of the first branch, both of which reached their maximum values near a critical density of 50,000 plants·ha^{-1}, likely influenced by physical soil limitations.

In the morphometric correlation analysis, plant height was positively associated with variables measured on the branch and leaf; in contrast, there was a negative association between the number of branches per plant and the number of leaves per branch. These associations reflect aspects related to the genetics and physiology of moringa, particularly its strong vertical growth habit at high growth rates.

Conflict of interest

LThe authors declare no conflict of interet at any stage of its publication.

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Declaration of author's contribution according to CRediT

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