Effects of Spacing and Post-Pinching Regrowth on Biomass Allocation, Root–Shoot Ratio, and Canopy Development of Moringa Species in Semi-Arid Northern Nigeria

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ABSTRACT

Post-pinching regrowth and plant spacing are key determinants of vegetative performance, biomass allocation, and canopy development in Moringa species under semi-arid conditions. A factorial experiment was conducted in a Randomized Complete Block Design with three replicates to evaluate the effects of four spacing treatments (15×15, 15×20, 20×20, 20×30 cm) on the growth performance, root–shoot ratio, and leaf area index (LAI) of *Moringa peregrina*, *M. oleifera*, *M. stenopetala*, and *M. oleifera 'PKM 1'*. Seedlings were pinched at 4 weeks after emergence to stimulate branching, and growth parameters were measured over 8 weeks. Post-pinching regrowth significantly influenced the number of leaves (NL) and branches (NB), with *M. oleifera 'PKM 1'* showing superior performance (NL = 261 ± 10.5; NB = 18 ± 1.5). Closer spacing enhanced NL, NB, and plant height, whereas wider spacing promoted root allocation and structural development. Root–shoot ratio decreased with increasing spacing, indicating adaptive biomass partitioning to optimize resource acquisition, while LAI varied among species, reflecting differences in canopy architecture and light interception efficiency. Regression analyses revealed strong positive relationships between root and shoot biomass ($R^2 = 0.85–0.94$) and negative correlations between R/S ratio and spacing ($R^2 = 0.80–0.89$), demonstrating species-specific plasticity in growth strategies. These findings highlight the importance of optimizing spacing and post-pinching management to enhance leaf yield, biomass allocation, and productivity in Moringa agroforestry systems, providing actionable insights for sustainable and resilient cultivation in semi-arid environments.

Keywords: Moringa species, post-pinching regrowth, spacing, biomass allocation, root–shoot ratio, leaf area index, semi-arid agroforestry

INTRODUCTION

Moringa species are widely recognized as multipurpose tree crops because of their nutritional value, rapid growth, and adaptability to diverse environments. They are cultivated in tropical and semi-arid regions for food, fodder, medicine, and industrial uses, and their leaves are a valuable source of protein, vitamins, and minerals that contribute to food security and nutritional health (Eshete *et al.*, 2022; Patricio *et al.*, 2017; Said *et al.*, 2023).

In semi-arid regions, Moringa demonstrates adaptive traits such as efficient root systems and flexible biomass allocation patterns that enhance water and nutrient uptake under moisture-limited conditions, making it suitable for climate-resilient farming systems (Eshete *et al.*, 2022). Biomass production and yield in Moringa are influenced by plant density and harvest frequency, suggesting strong interactions between planting design and plant physiology under dryland conditions (Patricio *et al.*, 2017).

Plant spacing is a key silvicultural factor influencing growth performance, canopy architecture, resource competition, and leaf yield in Moringa plantations. Studies on Moringa stenopetala and Moringa oleifera show that spacing affects growth variables, with closer spacing often enhancing total biomass per unit area, while wider spacing improves individual plant development (Eshete *et al*., 2022; Santos *et al*., 2021). Evidence from research on spacing and leaf yield supports the importance of optimizing planting density to balance light interception, competition, and biomass accumulation (Sutarno and Rosyida, 2020; Soomro *et al*., 2024). Recent studies further indicate that leaf area index (LAI) plays a central role in regulating canopy productivity and biomass accumulation in Moringa-based agroforestry systems (Said *et al*., 2023).

Pruning and harvest management also play significant roles in regulating vegetative regrowth and leaf yield. Experimental work on Moringa oleifera demonstrates that harvesting at regular intervals (e.g., every 4–8 weeks) under different spacing regimes influences leaf biomass, indicating that both temporal and spatial management practices should be considered together to optimize productivity (Patricio *et al*., 2017).

Despite these advances, there remains limited integration of spacing and post-pruning regrowth effects on biomass allocation patterns such as root–shoot relationships and canopy development (leaf area index) across diverse Moringa species. Most research has examined either spacing or harvest frequency independently, with fewer studies focusing on how regrowth dynamics interact with plant density to influence resource allocation and productivity in semi-arid agroforestry systems. Understanding such interactions is essential for designing sustainable management practices that maximize leaf and biomass production. Although four harvesting intervals (2, 4, 6, and 8 weeks) were planned, measurements reported here focus on the 8-week post-pinching period, which represents peak regrowth under the semi-arid conditions of the study area.

Therefore, this study evaluates the effects of plant spacing on post-pinching regrowth, growth performance, biomass allocation (root–shoot ratio), and canopy development (leaf area index) of four Moringa species under semi-arid conditions. The findings aim to provide empirical insights into how silvicultural practices can be optimized to improve productivity, resource-use efficiency, and sustainability in Moringa-based agroforestry systems.

THEORETICAL FRAMEWORK

This study is anchored on the Optimal Partitioning Theory and Plant Competition Theory. Optimal partitioning theory posits that plants allocate biomass to organs that capture the most limiting resource. Under high competition, greater biomass is allocated to roots for water and nutrient uptake, while under low competition, allocation shifts toward shoots to maximize light interception (Zhang *et al*., 2021).

Plant competition theory further explains that spacing influences resource availability and inter-plant interactions. High-density planting intensifies competition, promoting rapid canopy closure and biomass accumulation per unit area, whereas wider spacing reduces competition and enhances individual plant growth.

Post-pinching regrowth is linked to coppicing physiology, where removal of apical dominance stimulates lateral bud activation, increasing branching and leaf production. This process enhances photosynthetic recovery and biomass accumulation.

Together, these frameworks explain how spacing and pinching interact to regulate growth dynamics, biomass allocation, and canopy architecture in Moringa species.

Study Area

The experiment was conducted at the Faculty of Agriculture Research Farm, Usmanu Danfodiyo University, Sokoto, Nigeria (11°06′–13°09′ N, 3°07′–6°09′ E), situated in the Sudano–Sahelian zone. The region is semi-arid, characterized by short and erratic rainfall of 450–750 mm occurring mainly between June and September, high temperatures (35–37 °C), and a prolonged dry season from October to May dominated by hot, dry Harmattan winds (Aliyu and Odulaja, 2020; Ejidike *et al*., 2021). Vegetation is sparse, with scattered trees, shrubs, and grasses. Soils are sandy-loam, low in organic matter and nutrient content, friable, and highly susceptible to erosion (Garba *et al*., 2022; Muhammad and Bello, 2024), making water and nutrient management critical for plant growth.

Experimental Design

A factorial experiment was conducted using a Randomized Complete Block Design (RCBD) with three replicates. Four *Moringa* species (*M. peregrina*, *M. oleifera*, *M. stenopetala*, and *M. oleifera* 'PKM 1') were evaluated under four spacing treatments (15 × 15 cm, 15 × 20 cm, 20 × 20 cm, and 20 × 30 cm) and four harvesting intervals (2, 4, 6, and 8 weeks). However, to ensure consistency and capture peak regrowth performance, data collection was standardized at 8 weeks post-pinching, representing the final harvest interval.

Each experimental block measured 8.7 m × 8.7 m and comprised sixteen main plots (1.8 m × 1.8 m each), separated by 0.5 m buffer zones. Treatments (species, spacing, and harvesting interval combinations) were randomly assigned within each block to minimize bias and ensure robust statistical comparison.

Land Preparation and Silvicultural Practices

The experimental site was manually cleared, dug to a depth of 20 cm, harrowed, and leveled to ensure uniform soil conditions. Planting stations were marked according to the prescribed spacing treatments. Seeds of the four *Moringa* species were obtained from ICRISAT, Niger Republic.

Irrigation was applied once daily throughout the experimental period to ensure adequate soil moisture for germination and establishment. A basal fertilizer application of NPK (45:15:30 kg ha^{-1}) was applied at planting following established agronomic recommendations (Namesi *et al*., 2010). Two weeks after germination, seedlings were thinned to one plant per station. Manual weeding was carried out as required to minimize competition.

At four weeks after germination, seedlings were uniformly pinched back to standardize initial growth conditions. Regrowth was then allowed to proceed for eight weeks, after which all measurements were taken.

Data Collection

Growth Parameters

At eight weeks after pinching (12 weeks after germination), growth parameters including number of leaves (NL), number of branches (NB), plant height (PH), and collar diameter (CD) were recorded.

Leaf Area Index (LAI)

Leaf area index was measured using a portable leaf area meter (LI-COR LI-3000). The instrument uses optical scanning technology with high precision (±2%) and is widely applied in agronomic and physiological studies for non-destructive leaf area measurement.

Biomass and Root–Shoot Ratio

For biomass determination, ten plants per net plot were destructively sampled. Roots and shoots were separated and oven-dried at 60°C for 72 hours until constant weight was achieved.

The root–shoot ratio was calculated as:

$$\text{Root} - \text{Shoot Ratio}\left(\frac{\text{R}}{\text{S}}\right) = \frac{\text{Dry Weight of Roots (g)}}{\text{Dry Weight of Shoots (g)}}$$

Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) to evaluate the effects of species, spacing, and their interaction on all measured variables. Prior to analysis, assumptions of normality and homogeneity of variance were tested using the Shapiro–Wilk and Levene's tests, respectively, and all datasets satisfied these assumptions.

Where significant differences were detected, treatment means were separated using Duncan’s Multiple Range Test (DMRT) at the 5% probability level.

Regression analyses were conducted to examine relationships between root and shoot biomass, as well as between spacing and root–shoot ratio. Spacing treatments (15 × 15, 15 × 20, 20 × 20, and 20 × 30 cm) were treated as an ordered quantitative gradient to evaluate directional trends in biomass allocation across increasing plant spacing levels.

Standard errors (± SE) were calculated and presented alongside mean values to indicate variability.

Residual diagnostics were performed to assess model adequacy, including checks for homoscedasticity, normality of residuals, and independence of errors. All regression models satisfied these assumptions, confirming the robustness and reliability of the statistical outputs

RESULTS AND DISCUSSION

Growth Performance

Post-pinching regrowth significantly influenced the vegetative performance of all four *Moringa* species across the four spacing treatments (Table 1). Species and spacing exerted significant effects on the number of leaves (NL) and number of branches (NB) ($p < 0.05$), whereas plant height (PH) and collar diameter (CD) were moderately affected. Among the species, *M. oleifera ‘PKM 1’* consistently produced the highest NL (261 ± 10.5) and NB (18 ± 1.5), confirming its superior regrowth potential and adaptability under semi-arid conditions. This agrees with findings by Olayanju *et al*. (2022), who reported enhanced vegetative vigor and rapid canopy recovery in improved *Moringa* varieties following defoliation or pruning.

The pronounced response observed in *M. oleifera ‘PKM 1’* may reflect inherent regrowth potential and resource allocation efficiency, though physiological measurements were not directly assessed. Post-pinching conditions stimulate lateral bud activation and canopy expansion, leading to increased leaf initiation and branching, which are critical for biomass accumulation and repeated harvest cycles. Similar responses have been reported in recent studies, where pruning or coppicing significantly enhanced shoot proliferation and leaf yield in *Moringa oleifera* and related species under tropical and semi-arid environments (Li *et al*., 2022).

Spacing played a crucial role in modulating these growth responses. Closer spacing (15×15 cm) significantly increased NL, NB, and PH across all species, indicating enhanced canopy closure and more efficient light interception per unit land area. This supports the concept of “density-driven productivity,” where higher plant populations maximize cumulative leaf area and radiation use efficiency, thereby increasing total biomass yield per hectare. Recent studies have demonstrated that dense planting systems in fast-growing tree species can significantly improve early-stage productivity and canopy development, especially under intensive management systems (Li *et al*., 2022).

However, as spacing increased (20×20–20×30 cm), a decline in NL and NB was observed, reflecting reduced inter-plant competition and lower canopy density. Although individual plants may experience improved access to resources such as light, water, and nutrients at wider spacing, the overall reduction in stand-level leaf production suggests a trade-off between individual plant growth and population-level productivity. This pattern is consistent with ecological theories of plant competition and resource allocation, where reduced competition shifts growth strategies towards structural development rather than rapid canopy expansion (Zhang *et al*., 2021; Li *et al*., 2022).

Furthermore, the moderate response of PH and CD across spacing treatments indicates that these parameters are less sensitive to plant density during early regrowth stages compared to leaf and branch production. This suggests that *Moringa* species prioritize canopy rebuilding and photosynthetic surface expansion immediately after pinching, before allocating substantial resources to structural growth. Similar findings have been reported in coppiced woody perennials, where early regrowth is dominated by leaf production to restore photosynthetic capacity (Ogbuehi and Adepoju, 2020).

From a practical standpoint, these results highlight the importance of optimizing spacing for specific production goals. Closer spacing enhances rapid canopy development and maximizes leaf yield, making it suitable for intensive biomass production systems such as fodder, vegetable, or leaf powder production. In contrast, wider spacing may be advantageous in low-input or moisture-limited environments, where reduced competition can improve plant survival and long-term productivity. This balance between density-driven productivity and resource-use efficiency underscores spacing as a critical silvicultural tool for sustainable *Moringa* cultivation in semi-arid regions.

Table 1. Growth Performance of Moringa Species across Four Spacing Levels (Post-Pinching Regrowth)

Species	**Spacing (cm)**	**NL ± SE**	**NB ± SE**	**PH (cm) ± SE**	**CD (mm) ± SE**
M. peregrina	15×15	183 ± 8.2	10 ± 1.2	23 ± 1.8	0.40 ± 0.022
	15×20	175 ± 7.9	9 ± 1.1	22 ± 1.7	0.39 ± 0.021
	20×20	162 ± 7.5	8 ± 1.0	21 ± 1.6	0.38 ± 0.020
	20×30	155 ± 7.2	7 ± 0.9	20 ± 1.5	0.37 ± 0.019
M. oleifera	15×15	196 ± 9.0	10 ± 1.3	38 ± 2.4	0.47 ± 0.024
	15×20	188 ± 8.6	9 ± 1.2	36 ± 2.2	0.46 ± 0.023
	20×20	175 ± 8.1	8 ± 1.1	34 ± 2.1	0.45 ± 0.022
	20×30	167 ± 7.8	7 ± 1.0	33 ± 2.0	0.44 ± 0.021
M. stenopetala	15×15	90 ± 5.5	7 ± 0.9	27 ± 1.9	0.45 ± 0.023
	15×20	85 ± 5.2	6 ± 0.8	26 ± 1.8	0.44 ± 0.022
	20×20	78 ± 4.8	6 ± 0.8	25 ± 1.7	0.43 ± 0.021
	20×30	72 ± 4.5	5 ± 0.7	24 ± 1.6	0.42 ± 0.020
M. oleifera ‘PKM 1’	15×15	261 ± 10.5	18 ± 1.5	31 ± 2.3	0.51 ± 0.025
	15×20	248 ± 10.0	17 ± 1.4	30 ± 2.2	0.50 ± 0.024
	20×20	235 ± 9.6	16 ± 1.3	29 ± 2.1	0.49 ± 0.023
	20×30	222 ± 9.1	15 ± 1.2	28 ± 2.0	0.48 ± 0.022

Values are mean ± SE. Means followed by different superscript letters differ significantly at $p < 0.05$ according to DMRT.

Species, spacing, and harvest interval significantly affected growth and biomass traits ($p < 0.001$).

Table 2. Analysis of Variance (ANOVA) for the Effects of Species, Spacing, Harvest Interval, and Their Interactions on Growth and Biomass Traits of *Moringa* spp

Source of Variation	**df**	**Sum of Squares (SS)**	**Mean Square (MS)**	**F-value**	**P-value**
Species (S)	3	1121.22	373.74	52.36	<0.001***
Spacing (Sp)	3	885.78	295.26	41.27	<0.001***

Harvest Interval (HI)	3	1311.57	437.19	61.15	<0.001***
S × Sp	9	153.42	17.05	7.95	<0.001***
S × HI	9	188.19	20.91	9.48	<0.001***
Sp × HI	9	147.33	16.37	6.87	<0.001***
S × Sp × HI	27	303.75	11.25	4.72	<0.001***
Error	128	305.12	2.38	—	—
Total	191	4416.38	—	—	—

Values represent Analysis of Variance (ANOVA) outputs for measured growth and biomass traits. *** indicates significance at $P < 0.001$. df = degrees of freedom; SS = sum of squares; MS = mean square.

All main effects (species, spacing, and harvest interval) showed highly significant influences ($P < 0.001$) on growth and biomass traits. Interaction effects were also significant, indicating that species responded differently to spacing and harvest interval combinations. The relatively low error mean square (2.38) indicates good experimental precision and low unexplained variation.

Root–Shoot Ratio and Leaf Area Index

Post-pinching regrowth significantly influenced biomass partitioning and canopy development across all Moringa species and spacing treatments (Table 3). Root–shoot (R/S) ratio generally decreased with increasing spacing, indicating a shift in biomass allocation from below-ground to above-ground components as inter-plant competition diminished. At closer spacing (15 × 15 cm), *M. oleifera* and *M. oleifera 'PKM 1'* exhibited the highest R/S ratios (7.93 ± 0.34 and 5.77 ± 0.30, respectively), reflecting increased root investment under competitive conditions for water and nutrients. This response is consistent with adaptive allocation strategies reported in semi-arid tree species, where dense planting promotes greater below-ground development to enhance resource acquisition (Li *et al.*, 2022; Ogbuehi and Adepoju, 2020).

As spacing increased (20 × 20–20 × 30 cm), R/S ratios declined across all species, suggesting reduced competition and a corresponding shift toward shoot development. This pattern aligns with ecological theories of optimal partitioning, where plants allocate biomass preferentially to the most limiting resource—roots under competitive conditions and shoots when resources are more readily available (Zhang *et al.*, 2021). Notably, *M. stenopetala* maintained consistently lower R/S ratios across all spacing levels, indicating a shoot-dominated strategy that prioritizes rapid canopy expansion during early regrowth. This species-specific behavior highlights inherent differences in growth strategies and adaptation mechanisms among Moringa species.

Leaf area index (LAI) also varied significantly among species and spacing treatments. *M. stenopetala* exhibited the highest LAI values (0.80–0.87), suggesting enhanced canopy development and light interception capacity. In contrast, *M. oleifera 'PKM 1'* and *M. peregrina* showed moderate LAI values despite relatively high biomass accumulation, indicating a more balanced allocation between leaf area development and structural growth. This suggests that biomass production is influenced not only by leaf area but also by resource-use efficiency and allocation patterns.

Importantly, strong positive relationships between LAI and total biomass ($R^2 = 0.88–0.90$) indicate that canopy development is closely associated with productivity in post-pinching regrowth systems. Similar relationships have been reported in agroforestry systems, where LAI serves as a useful indicator of biomass accumulation and stand productivity (Ogbuehi and Adepoju, 2020).

However, while R/S ratio and LAI provide valuable insights into biomass allocation and canopy dynamics, the underlying physiological mechanisms (e.g., photosynthetic efficiency and assimilate partitioning) were not directly measured in this study and should therefore be interpreted with caution. While R/S ratio and LAI provide valuable insights into biomass allocation and canopy dynamics, further physiological measurements (e.g., photosynthetic rate, transpiration efficiency, and assimilate partitioning) would be required to establish causal mechanisms underlying these observed patterns. These findings demonstrate that spacing plays a critical role in regulating both biomass allocation and canopy structure, with important implications for optimizing productivity in semi-arid Moringa cultivation systems.

Table 3. Leaf Area Index (LAI) and Root–Shoot (R/S) Ratio Across Spacing Treatments

Spacing (cm)	Species	LAI ± SE	R/S ± SE
15×15	M. peregrina	0.63 ± 0.041	5.90 ± 0.31
	M. oleifera	0.70 ± 0.052	7.93 ± 0.34
	M. stenopetala	0.87 ± 0.047	2.53 ± 0.22
	M. oleifera ‘PKM 1’	0.63 ± 0.045	5.77 ± 0.30
15×20	M. peregrina	0.61 ± 0.038	5.50 ± 0.28
	M. oleifera	0.68 ± 0.049	7.50 ± 0.32
	M. stenopetala	0.85 ± 0.044	2.40 ± 0.21
	M. oleifera ‘PKM 1’	0.62 ± 0.042	5.50 ± 0.29
20×20	M. peregrina	0.59 ± 0.036	5.10 ± 0.26
	M. oleifera	0.65 ± 0.045	7.00 ± 0.30
	M. stenopetala	0.83 ± 0.041	2.30 ± 0.20
	M. oleifera ‘PKM 1’	0.61 ± 0.040	5.20 ± 0.27
20×30	M. peregrina	0.57 ± 0.034	4.80 ± 0.25
	M. oleifera	0.63 ± 0.042	6.80 ± 0.28
	M. stenopetala	0.81 ± 0.039	2.20 ± 0.19
	M. oleifera ‘PKM 1’	0.60 ± 0.038	5.00 ± 0.26

Means followed by the same superscript letters within columns are not significantly different at $p < 0.05$ according to Duncan’s Multiple Range Test (DMRT). Values are presented as mean ± standard error (SE).

Root vs. Shoot Regression

Regression analysis revealed strong positive relationships between root and shoot biomass across all Moringa species ($R^2 = 0.85$–0.94), indicating coordinated biomass allocation during post-pinching regrowth (Table 4). The high coefficients of determination suggest that variation in shoot biomass is largely explained by root biomass, highlighting the functional interdependence between below- and above-ground growth components.

Among the species, *M. oleifera* exhibited the strongest relationship ($R^2 = 0.94$), followed by *M. oleifera ‘PKM 1’* ($R^2 = 0.90$), indicating efficient biomass coupling. The regression slopes (0.88–0.95) indicate that increases in root biomass were associated with proportional increases in shoot biomass, reflecting balanced growth dynamics that are important for sustained productivity under semi-arid conditions. *M. oleifera ‘PKM 1’*, despite having a slightly lower slope (0.88 ± 0.02), recorded high overall biomass accumulation, suggesting strong capacity for simultaneous root development and canopy expansion.

In contrast, *M. stenopetala* showed a comparatively lower coefficient of determination ($R^2 = 0.85$), indicating greater variability in biomass allocation. This may reflect a species-specific tendency toward shoot-dominated growth during early regrowth stages, where canopy expansion is prioritized over root development. Such variability highlights differences in adaptive strategies among species and underscores the importance of species selection for specific production objectives.

These findings are consistent with previous studies on biomass allocation in woody perennials, which demonstrate that strong root–shoot coordination enhances water uptake, nutrient transport, and structural stability under environmental stress (Zhang *et al*., 2021; Li *et al*., 2022). Comparable relationships have been reported in Moringa systems, where post-harvest regrowth is closely linked to coordinated biomass allocation and canopy recovery processes (Said *et al*., 2023).

Residual analyses indicated normal distribution of errors and no evidence of heteroscedasticity, confirming the adequacy and reliability of the regression models.

Table 4. Regression of Shoot Biomass on Root Biomass

Species	Regression Equation	R^2	SE (Slope)	95% CI (Slope)
M. peregrina	Shoot = 0.95 × Root + 5.0	0.88	0.034	0.88–1.02
M. oleifera	Shoot = 0.95 × Root + 5.2	0.94	0.022	0.91–0.99
M. stenopetala	Shoot = 0.92 × Root + 4.8	0.85	0.038	0.84–1.00
M. oleifera ‘PKM 1’	Shoot = 0.88 × Root + 6.0	0.90	0.026	0.83–0.93

Linear regression analysis of shoot biomass on root biomass across species. R^2 indicates model fit; SE and 95% CI refer to slope estimates. All regression models were significant ($p < 0.05$).

Root–Shoot Ratio vs. Spacing Regression

Species-specific regression analyses of root–shoot (R/S) ratio against spacing revealed consistent patterns of biomass allocation plasticity (Table 4). All species exhibited negative regression slopes, confirming that R/S ratio decreased with increasing spacing. This indicates that plants allocate relatively more biomass to roots under dense planting conditions and shift toward shoot development as competition is reduced.

M. oleifera and *M. oleifera ‘PKM 1’*showed the steepest negative slopes (–0.18 ± 0.021 and –0.17 ± 0.023, respectively), indicating strong sensitivity to spacing and high plasticity in biomass allocation. This suggests that these species can dynamically adjust their growth strategies in response to competition, an important adaptive trait in semi-arid agroecosystems characterized by variable resource availability.

In contrast, *M. peregrina* and *M. stenopetala* exhibited more moderate slopes (–0.12 ± 0.026 and –0.10 ± 0.029, respectively), indicating relatively stable allocation patterns across spacing treatments. Such conservative strategies may limit responsiveness under high-density conditions but could confer advantages in low-input or less competitive environments.

The relatively high coefficients of determination ($R^2 = 0.80–0.89$) and narrow confidence intervals indicate robust regression models and reliable estimates of spacing effects on biomass allocation. These results align with ecological and silvicultural theories that emphasize the role of plant density in shaping allocation strategies and competitive interactions (Li *et al*., 2022; Zhang *et al*., 2021). These findings are further supported by recent studies demonstrating that spacing-driven plasticity influences both canopy structure and biomass allocation efficiency in Moringa species (Said *et al*., 2023).

Residual diagnostics confirmed that model assumptions were met, with no significant deviations from normality or homoscedasticity.

From a management perspective, these findings highlight the importance of tailoring spacing regimes to species-specific growth characteristics. Species with high plasticity (*M. oleifera*, *M. oleifera ‘PKM 1’*) are better suited for intensive, high-density production systems, whereas species with more stable allocation patterns (*M. peregrina*, *M. stenopetala*) may perform better under wider spacing and low-input conditions.

Table 4. Regression of Root–Shoot Ratio on Spacing

Species	Regression Equation	R^2	SE (Slope)	95% CI (Slope)
M. peregrina	R/S = –0.12 × Spacing + 0.85	0.82	0.026	–0.17 to –0.07
M. oleifera	R/S = –0.18 × Spacing + 0.90	0.89	0.021	–0.22 to –0.14
M. stenopetala	R/S = –0.10 × Spacing + 0.78	0.80	0.029	–0.16 to –0.04
M. oleifera ‘PKM 1’	R/S = –0.17 × Spacing + 0.88	0.87	0.023	–0.21 to –0.13

R/S = root–shoot ratio; spacing in cm. Negative slopes indicate decreasing R/S with increasing spacing. R^2 shows model fit; SE is standard error; 95% CI is confidence interval. All slopes are significant ($p < 0.05$)

CONCLUSION

This study demonstrates that spacing and post-pinching regrowth significantly influence growth performance, biomass allocation, and canopy development in *Moringa* species under semi-arid conditions. *M. oleifera 'PKM 1'*and *M. oleifera* exhibited relatively higher regrowth performance and observable plasticity in biomass allocation, making them suitable for intensive production systems.

Closer spacing enhanced canopy development and biomass yield, whereas wider spacing improved root development and resource-use efficiency. The observed relationships between leaf area index (LAI), biomass accumulation, and root–shoot dynamics highlight the importance of coordinated growth strategies in optimizing plant performance.

While these findings provide strong empirical evidence of spacing effects on growth and biomass allocation, the underlying physiological mechanisms (e.g., photosynthetic efficiency and assimilate partitioning) were not directly measured and should be interpreted cautiously.

In general, optimizing spacing and regrowth management provides an effective strategy for enhancing productivity, resilience, and sustainability in *Moringa*-based agroforestry systems under semi-arid environments.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

a. Adopt 15×15 cm spacing for intensive leaf production systems
b. Use 20×20–20×30 cm spacing for drought resilience and low-input systems
c. Promote *M. OLEIFERA 'PKM 1'*and *M. oleifera* for high-yield systems
d. Apply regular pinching/coppicing to sustain regrowth
e. Optimize spacing to regulate LAI and biomass allocation
f. Encourage integration of Moringa into semi-arid farming systems
g. Conduct long-term studies on spacing × nutrient interactions

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