PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–09
https://doi.org/10.14719/pst.5487

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RESEARCH ARTICLE

Strategic agronomic interventions for leaf yield and quality improvement in Moringa (*Moringa oleifera* L.) under High Density Planting System

M P Kavitha[1*], R Balakumbahan[2], M Uma Maheswari[2], G Sidhdharth[2], K Nageswari[2], G Sudhakar[1], C Parameswari[1], M Madhan Mohan[1] & Jawahar Desigan[3]

[1]Agricultural Research Station, Tamil Nadu Agricultural University Vaigai Dam, Theni 625 562, India

[2]Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam 625 604, India

[3]Department of Genetics and Plant Breeding, V.O.C Agricultural college & Research Institute, Killikulam, TNAU, Coimbatore 628 252, Tamil Nadu

*Email: kavitha.mp@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 05 October 2024
Accepted: 02 November 2024
Available online
Version 1.0 : 24 December 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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CITE THIS ARTICLE
Kavitha MP, Balakumbahan R, Maheswari UM, Sidhdharth G, Nageswari K, Sudhakar G, Parameswari C, Mohan MM, Designan J. Strategic agronomic interventions for leaf yield and quality improvement in Moringa (*Moringa oleifera* L.) under High Density Planting System. Plant Science Today.2024;11(sp4):01-09.
https://doi.org/10.14719/pst.5487

Abstract

Moringa leaves are rich in minerals, vitamins, proteins, and soluble fiber, making them an ideal dietary supplement for addressing undernourishment, as well as iron and vitamin A deficiencies. The presence of high concentrations of potassium, iron, calcium and magnesium and natural antioxidants are particularly beneficial for pregnant mothers and young children. The current study carried out in 2021 and 2022, sought to standardize crop geometry and harvesting heights to enhance leaf biomass and quality in *Moringa* under High-Density Planting Systems .

The research trial employed four different spacing configurations, incorporating single-row and double-row triangular planting at both wider and closer spacing and included three harvesting heights. The experiment was arranged in a split-plot design with three replications. Observations on growth parameters, physiological traits and yield characters were recorded at each harvest. Leaf quality parameters were analyzed in dried *Moringa* leaf powder. Pooled results indicated that double-row triangular planting with narrower intra-row spacing, combined with a 45 cm harvesting height, yielded substantially higher fresh and dried leaf yields of 42.76 t/ha and 7.83 t/ha, respectively. This treatment also produced superior leaf quality parameters, attributed to enhanced growth, physiological responses and yield outcomes, leading to greater economic returns through enhanced fresh leaf yield.

Keywords

Moringa; triangle planting; leaf yield; quality; economic returns

Introduction

Moringa (*Moringa oleifera*) is a perennial, deciduous tree within the Moringaceae family. Distinguished for its swift growth and drought resistance, it is mostly cultivated in India for its edible pods, ben oil, fodder and medicinal properties. At present, *Moringa* leaves have gained popularity among cultivators due to their superior nutritional attributes. (1) *Moringa* leaves are abundant in vitamins, minerals, proteins and soluble dietary fiber. They serve as an exemplary dietary supplement for addressing malnutrition and deficiencies in iron and vitamin A (2). The leaves exhibit a high concentration of iron, potassium, calcium, phosphorus, antioxidants and beta-carotene, making them particularly beneficial for expectant mothers and young children (3). Vitamin C, vitamin A, crude fiber and crude protein in *Moringa* foliage significantly impede and neutralize free radicals, thereby offering protection to humans against pathogens and degenerative ailments (4). *Moringa* leaf powder is utilized in the nutraceutical and pharmaceutical sectors. High levels of iron found in *moringa* leaves is advantageous in managing anemia. *Moringa* leaves are utilized as a nutritional supplement for both poultry and livestock. The incorporation of *Moringa* leaves into animal feed has been shown to enhance animal health, nutritional status, weight gain, milk production and digestibility and resistance to parasitic infestations. Approximately eighty percent of *moringa* leaves production is vital in augmenting foreign exchange earnings for the national economy. With an annual growth rate of 26 to 30 percent, the exportation of *moringa* leaves represents a significant commercial enterprise in Indian states, particularly Odisha, Tamil Nadu, Andhra Pradesh and Karnataka. The principal nations that import *moringa* leaves include China, the United States, Germany, Canada, South Korea and European countries. India is, the preeminent *Moringa* supplier at an international level, meeting approximately 80 percent of the global demand.

The increase in yield of *Moringa* leaves per unit area is crucial to meet the rising demand for Moringa leaves and associated leaf products . This objective is expected to be realized by implementing a High-Density Planting System (HDPS) analogous to those employed in fruit crops, complemented by appropriate management practices. Applying HDPS in *Moringa* cultivation will facilitate intercultural operations and increase yield and economic returns per unit area. The height at which *Moringa* is harvested is crucial for mechanization, as various quality parameters of the leaves fluctuate with differing harvesting heights. Current studies on the relationship between crop geometry and harvesting heights to optimize leaf yield are scarce. This study concentrates on the annual *Moringa* variety PKM 1, aiming to establish the optimal crop geometry suitable for high-density planting and to determine the ideal harvesting heights for producing superior-quality *moringa* leaves.

Materials

The research trial was conducted at the Horticultural College and Research Institute, Periyakulam, Tamil Nadu, from 2021 to 2022, to optimize crop geometry and harvesting heights to enhance *moringa* leaf biomass and quality. The experimental site was located at coordinates 10^0.13'N, 77^0.59' E, at an altitude of 289 M, with an average annual rainfall of 791.1 mm. The experiment utilized a split-plot design featuring four main plot treatments with varying crop geometries: M_1- 150 cm x 25 cm, M_2-150 cm x 50 cm, M_3- 150 cm x 25 cm x 25 cm and M_4- 150 cm x 50 cm x 50 cm, alongside three subplot treatments based on different harvesting heights: S_1 - 30 cm, S_2 - 45 cm, S_3 - 60 cm, each replicated three times.

The annual *moringa* variety PKM 1 was sown with a seed rate of 4-5 kg per hectare used for leaf production. Seeds were planted according to the defined treatment structure. Normal planting employed crop geometries of 150 cm x 25 cm and 150 cm x 50 cm, while high-density planting utilized triangular arrangements in double rows for the geometries of 150 cm x 25 cm x 25 cm and 150 cm x 50 cm x 50 cm. (Fig 1 and Fig 2). Drip irrigation was utilized to promote equitable water distribution and enhance irrigation efficiency. Irrigation commenced post-seed sowing, ensuring optimal soil moisture and supporting consistent germination and seedling establishment during the initial 8-10 days. An irrigation interval of five days was followed and adjusted based on the prevailing climatic conditions during the study.

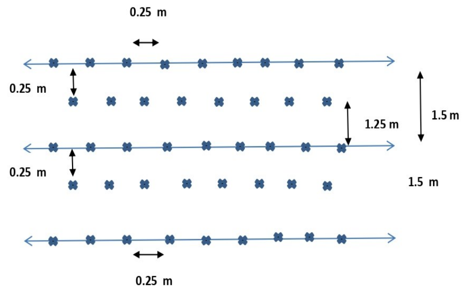

Fig 1. Double row triangle planting with 150 cm x 25 cm x 25 cm (53,332plants/ha)

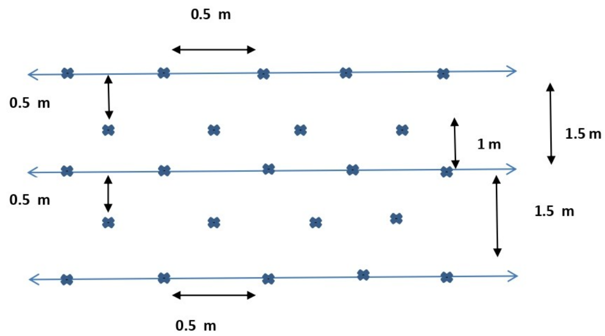

Fig 2. Double row triangle planting with 150 cm x 50 cm x 50 cm (26,666 plants/ha)

Five tonnes of vermicompost and 45 kg P_2O_5 were applied as basal doses to enhance the leaf production. To improve biomass yield and fertilizer efficiency, 275 kg N and 90 kg K_2O were applied in five splits, repeated in the subsequent year. Biofertilizers, such as Azospirillum, Phosphobacteria, and AM Fungi at a rate of 2 kg/ha/year, were employed to boost crop development. Early weeds were managed through pre-emergence application of pendimethalin. Inter-row weeds were subsequently controlled through mechanical weeding, while weeds around plants were removed manually. Plant tip-pinching was followed 15 days after germination to encourage lateral shoot proliferation. To prevent lodging, soil earthing around plant bases was performed 3 to 4 times annually.

Moringa leaves were ready for harvest 70 - 80 days after sowing. The subplot treatments included harvesting at heights of 30 cm, 45 cm and 60 cm above the soil surface. Subsequent harvests were conducted at intervals of 40 days. Harvested leaves were transferred to a well-ventilated, partially shaded environment for drying. Periodical stirring was followed to facilitate adequate drying and reduce the moisture content in freshly harvested *Moringa* leaves.

Methods

Analyses of *Moringa* growth metrics, including plant height, total primary branches, count of compound leaves, and stem circumference, were recorded at the initial harvest. Plant height was measured on randomly tagged plants from the base of the plant (ground level) to the top using a meter scale, and the mean was calculated. The number of primary branches arising from the trunk was recorded by visual counting and expressed in numbers. From the second harvest onwards, lateral branches, called secondary branches, were recorded and expressed in numbers. The number of whole leaves (with rachis) was visually counted and expressed as the count of compound leaves. Stem girth was measured 10 cm above ground level on all tagged plants using thread and a meter scale. The mean was calculated and expressed in centimetres.

During the study period, physiological attributes, viz., light interception percentage (Lux meter), total chlorophyll content, leaf area, crop growth rate and relative growth rate.

Light intensity was measured using Lux meter and calculated using the following formula.

$$\text{Light Interception (\%)} = \frac{\text{Light intensity in open (Lux) - Average intensity in crop (Lux)}}{\text{Light intensity in open (Lux)}}$$

Total chlorophyll content was estimated using a spectrophotometer as per the procedure given by (5). The mean was calculated and expressed in milligrams per gram.

$$\text{Total chlorophyll} = \frac{\text{OD@ 652 nm} \times V}{34.5 \times W}$$

where, V = volume made and W = weight of the leaf sample

Leaflet area was calculated using the linear measurement method and expressed in cm^2.

Fresh and dry leaf yields per hectare were calculated for each treatment combination in each harvest, with the total expressed in tonnes per hectare. The ratio of fresh to dry leaf recovery was calculated by dividing the fresh weight of the leaflets by their dry weight for each treatment combination.

Leaf quality attributes, including mineral content (potassium, iron, zinc, manganese calcium, magnesium), vitamin A, ascorbic acid, crude fiber and crude protein content, were analyzed in *Moringa* leaf powder using the standard procedures. Potassium content was estimated using a flame photometer as per the procedure given by (6). Iron and zinc content in the leaf samples were estimated using an atomic absorption spectrophotometer according to Stanford (6). Manganese content was estimated using an Atomic absorption spectrophotometer according to Jackson (7). Calcium and Magnesium were estimated by titration with a standardized EDTA solution.

Vitamin A content in leaf samples was estimated using a spectrophotometer as per the procedure of Jensen (8). Ascorbic acid content was estimated following the procedure given by (9). The amount of crude fiber was estimated by the muslin cloth method (10). Crude protein was estimated using the following formula,

Crude protein (%) = Nitrogen (%) X 6.25

During the study period, a total of nine harvests were completed. Pooled analysis was done and tabulated. The collected empirical data underwent rigorous statistical analysis to ascertain the significance of the differences among the various treatment combinations (11). A cost-effectiveness analysis was conducted to evaluate the economic viability of the treatment combinations.

Results and Discussion

Influence of Agronomic interventions on growth attributes

Plant height : Crop geometry is a main factor in determining crop yield. Plant density refers to the number of plants accommodated in a unit area. The cultivation of *Moringa* for leaf production mostly relies on precise manipulation of plant density. Optimal management of plant density is vital for the efficient utilization of nutrients, irrigation and light, leading to robust crop development and maximum biomass production (12).

Irrespective of planting methods, when the moringa was planted with a closer intra-row spacing of 25 cm, it recorded a significantly greater plant height to a wider intra-row spacing of 50 cm. Harvesting at a height of 60 cm resulted in a higher plant height than at 30 cm and 45 cm, as the topmost cut was made, thereby contributing to an increase in plant height (Table 1). In closer spacing, greater competition for light exists among the plants, leading to competition for light in high-density planting, as reported by (13). Etiolation enhances a plant's ability to locate light sources. Under etiolation, the growing tips exhibit a pronounced phototropic response, leading to elongation. Additionally, etiolation promoted increased internodal length, contributing to the greater height of the plants.

Table 1. Influence of Agronomic interventions on plant height (cm) in moringa

Harvesting heights (cm)	Crop geometry				
	M1	M2	M3	M4	Mean
S1 - 30 cm	142.8	134.8	130.8	138.7	136.7
S2 - 45 cm	145.9	132.8	156.2	144.6	144.8
S3 - 60 cm	152.7	137.5	164.8	149.1	151.1
Mean	147.14	135.04	150.62	144.16	
	M	**S**	**M x S**	**S x M**	
SEd	3.6	2.5	5.9	7.9	
CD (P= 0.05)	7.8	5.9	12.5	16.8	

Primary and secondary branches: Primary branches were identified and quantified from the main stem nodes. Greater quantities of primary branches were noted with wider spacing, regardless of whether single or double-row planting was employed, compared to closer planting. Single -row planting with a crop geometry of 150 cm x 150 cm yielded the highest number of primary branches (4.09), followed by triangle planting in a double row with a configuration of 150 cm x 150 cm x 150 cm (3.81). The minimum number of branches (2.63) was recorded with the closer intra-row spacing of 150 cm x 25 cm x 25 cm (Fig 3).

Similarly, secondary branches were significantly more abundant with wider spacing, paralleling the trend observed in primary branches across both planting methods. The highest number of secondary branches (8.28) was recorded with a crop geometry of 150 cm x 50 cm, followed by 150 cm x 150 cm x 150 cm (Fig 3). An increase in both primary and secondary branches under wider spacing in *moringa* leaf production was reported by (12). The maximum count of secondary branches registered at a harvesting height of 45 cm, closely followed by 60 cm.

Count of Compound leaves: The total number of compound leaves was lower with the crop arrangement of 150 cm x 50 cm (Fig 3). An increase in plant height was correlated with an augmented number of compound leaves in the denser crop configuration utilizing triangular planting at 150 cm x 25 cm x 25 cm. The highest number of compound leaves was observed at a harvesting height of 45 cm compared to other harvesting heights.

Stem Girth: A significantly greater stem circumference was observed in broader crop configurations, particularly with single and double-row planting arrangements at wider spacing. The broader crop geometry of 150 cm x 50 cm yielded a stem circumference of 11.33 cm, followed closely by the 150 cm x 50 cm x 50 cm configuration, which measured 11.00 cm. Due to reduced competition for resources, plants exhibited enhanced stem girth in wider spacing, regardless of single or double-row arrangements. The smallest stem girth was noted in the narrower crop configuration of 150 cm x 25 cm x 25 cm (Fig 4). Lower stem girth in closer proximity settings is primarily due to increased competition, which leads to suboptimal stem development. Similar findings were reported by Maheswari et al. (14) in cotton.

Influence of agronomic interventions on physiological characteristics

Total chlorophyll: Chlorophylls, the chromophores responsible for absorbing and converting solar energy into chemical energy, show a unique pattern in their aggregation within plant species. Significantly higher total chlorophyll contents of 49.69 mg/100g and 44.62 mg/100g were registered under wider spacing with single-row planting at 150 cm x 50 cm and double-row planting with triangular arrangements of 150 cm x 50 cm x 50 cm, respectively, compared to closer crop geometries. (Fig 4). The elevated chlorophyll index observed with wider row spacing may be attributed to an augmented concentration of foliar pigments. The optimal sunlight availability and enhanced aeration associated with wider spacing promote photosynthesis more effectively, enhancing chlorophyll content. These findings are consistent with the research conducted by (15).

Crop Growth Rate: Crop Growth Rate (CGR) refers to the change in dry weight in a certain time span. The highest CGR of 6.80g /m2/day was registered with triangle planting in a narrower arrangement of 150 cm x 25 cm x25 cm. This was followed by triangular planting with a spacing of 150 cm x 50 cm x 50 cm, which recorded 1.02 g /m^2/day, and closely by the plant geometry of 150 cm x 25 cm, which recorded 0.95 g /m^2/day (Table 2.) Research findings corroborate the findings of Basra et al. (16) in *Moringa* and Maheswari et al. (14) in cotton. The influence of subplot treatment had a significant impact on crop growth rate.

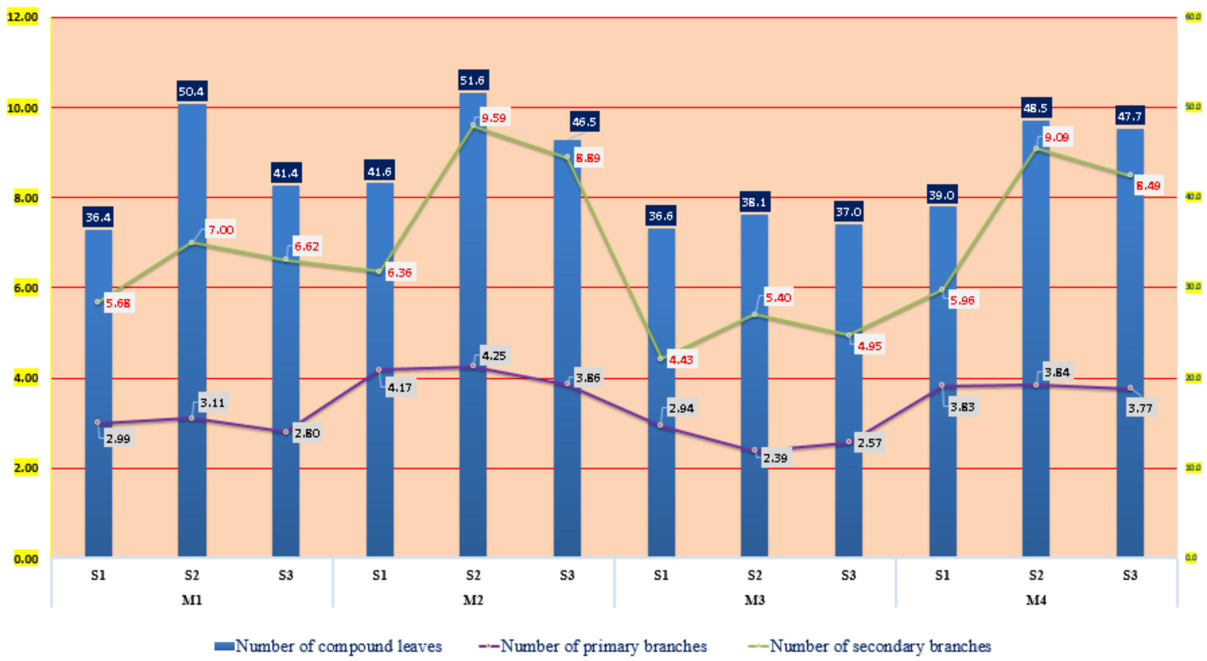

Fig 3. Influence of crop geometry and harvesting height on growth characteristics of *Moringa* under HDPS

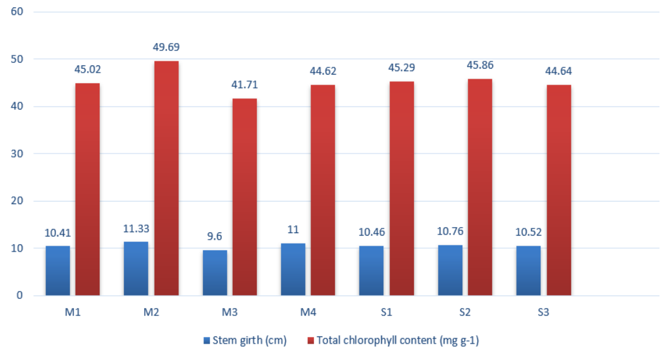

Fig 4. Influence of crop geometry and harvesting height on stem girth (cm) and total chlorophyll content (mg g^{-1}) of moringa under HDPS

A harvesting height of 45 cm registered a higher CGR, 2.83 g /m^2/day, compared to the harvesting height of 60 cm, which recorded 2.72 g $m^{-2}day^{-1}$ g /m^2/day. This may be related to the greater dry matter production associated with these treatments. The treatment combination of triangular planting with a spacing of 150 cm x 25 cm x 25 cm and a harvesting height of 45cm showed the highest crop growth rate at 9.12 g /m^2/day, followed by triangular planting with the same spacing and a harvesting height of 60cm (8.68 g / m^2/day) (Table 2).

Relative Growth Rate (RGR): RGR is defined as the increase in dry weight over a given period relative to the initial weight. Triangle planting with a narrow intra-row geometry of 150 cm x 25 cm x 25 cm showed a greater RGR of 0.0028g/ g /day, followed by a crop geometry of 150 cm x50 cm x 50 cm, which recorded a 0.0022g/g /day. A harvesting height of 60 cm registered a higher RGR of 0.0023 g/g /day, closely followed by a harvesting height of 45 cm, which recorded 0.0022 g/g /day. The treatment combination of double-row triangular planting with a narrow crop geometry of 150 cm x25 cm x 25cm and a harvesting height of 60 cm showed the highest RGR at 0.0037 g/g /day, followed by the treatment combination of the same plant geometry with a harvesting height of 45 cm (Table 2).

Leaflet area: Single-row planting with a wider crop geometry of 1.50 m x 0.50 recorded the maximum leaflet area of 1.33 cm^2, followed by double-row triangular planting with a wider crop geometry. The wider spacing resulted in higher chlorophyll content due to increased photosynthetic activity, which prompted greater leaf growth and increased leaflet area. At lowest plant densities, plants grow without competition, allowing leaves to develop into a larger size. The same was also stated by Bhattarai et al. (17) in cherry tomato, Bagri et al. (13) in Cape Gooseberry, 18. Nandeshwar et al. (18) in chilli and Teshale and Tekeste (19) in garlic. Harvesting heights and the interaction between crop geometry and harvesting heights had no significant impact on leaflet area among treatments (Table 2).

Light interception : The light interception was markedly affected by the agricultural configurations employed in cultivating *Moringa* leaves. Among the crop geometries examined, single-row planting with a broader spacing of 150 cm x 50 cm resulted in the highest level of light interception (10.95) due to the reduced number of plants per unit area, which allows for unimpeded growth without competition for sunlight. Consequently, light penetrates more effectively in areas with wider spacing. Conversely, closer spacing results in competition for light, leading to the lowest levels of light interception in densely populated arrangements.

Regarding harvesting heights, interception was highest at 30 cm compared to other heights (Table 2). The combination of the crop geometry of 150 cm x 50 cm with a harvesting height of 30 cm yielded the highest recorded light interception at 11.70 %. This phenomenon may be attributed to the treatment's ability to maintain lower biomass cover, thereby mitigating competition for light, as reported by (2).

Influence of agronomic interventions on the leaf yield of Moringa

Fresh leaf yield : The configuration of cultivation and harvesting height techniques have been shown to exert a notable effect on the primary leaf yield of *moringa*. A total of nine harvests of *Moringa* leaves were completed during the two-year research endeavor. The biomass of *moringa* leaves from all nine harvests was aggregated and systematically presented in tabular form. The triangular planting configuration with a denser crop geometry of 150 cm x 25 cm x 25 cm registered an elevated fresh leaf yield of 40.61 t/ ha, followed by the configuration of 150 cm x 50 cm x 50 cm (Table 3). The lowest fresh leaf yield was observed in the single-row, wider 150 cm x 50 cm arrangement. Notably, a significantly higher fresh leaf yield was recorded at a

Table 2. Influence of Agronomic interventions on physiological characteristics in Moringa

	CGR (g/ m^2/day)					RGR (g/g/day)				
	M1	M2	M3	M4	Mean	M1	M2	M3	M4	Mean
S1	0.81	0.18	2.60	0.93	1.13	0.0018	0.0011	0.0010	0.0019	0.0015
S2	1.02	0.12	9.12	1.05	2.83	0.0023	0.0007	0.0036	0.0022	0.0022
S3	1.03	0.12	8.68	1.07	2.72	0.0023	0.0007	0.0037	0.0023	0.0023
Mean	0.95	0.14	6.80	1.02	2.23	0.0021	0.0008	0.0028	0.0022	0.0020
	M	S	M x S	S x M		M	S	M x S	S x M	
SEd	0.34	0.26	0.52	0.79		0.0003	0.0003	0.0006	0.0008	
CD (P=0.05)	0.84	0.55	1.10	1.82		0.0008	0.0006	0.0013	0.0019	
	Leaflet area (cm2)					Light interception (%)				
	M1	M2	M3	M4	Mean	M1	M2	M3	M4	Mean
S1	1.05	1.31	0.86	1.18	1.10	8.03	11.70	6.56	7.00	8.32
S2	1.23	1.34	1.03	1.30	1.22	6.90	10.51	6.18	6.42	7.50
S3	1.29	1.33	0.90	1.24	1.19	7.57	10.64	6.32	6.68	7.80
Mean	1.19	1.33	0.93	1.24	1.17	7.50	10.95	6.35	6.70	
	M	S	M x S	S x M		M	S	M x S	S x M	
SEd	0.03	0.08	0.15	0.17		0.32	0.10	0.21	0.60	
CD (P=0.05)	0.09		NS			0.79	0.22	0.44	1.44	

Table 3. Influence of agronomic interventions on fresh leaf biomass and dry leaf yield (tons/ha) (Pooled yield of nine harvests)

Treatments	Fresh leaf biomass (tonnes/ha)				
	M1	M2	M3	M4	Mean
S1 – 30 cm	27.52	19.54	38.87	29.13	28.77
S2 - 45 cm	27.72	20.98	42.76	29.57	30.26
S3 - 60 cm	27.29	19.53	40.20	29.34	29.09
Mean	27.510	20.02	40.61	29.35	
	M	S	M x S	S x M	
SEd	0.530	0.95	1.90	2.11	
CD (P= 0.05)	1.298	2.01	4.03	4.61	

Treatments	Dry leaf yield (tonnes/ha)				
	M1	M2	M3	M4	Mean
S1 - 30 cm	5.12	3.58	7.13	5.32	5.29
S2 - 45 cm	5.32	3.89	7.83	5.53	5.64
S3 - 60 cm	4.99	3.60	7.35	5.46	5.35
Mean	5.08	3.69	7.44	5.44	
	M	S	M x S	S x M	
SEd	0.10	0.18	0.36	0.40	
CD(P= 0.05)	0.25	0.39	0.76	0.88	

harvesting height of 45 cm, amounting to 30.25 t. Denser spacing allows for more plants, while wider spacing accommodates fewer. A denser layout enhances plant population, hence improving production in such arrangements. These results align with the findings of Basra et al. (16) and Abdullahi et al. (20). Adegun and Ayodele (21) reported that *Moringa* biomass output was highest at the denser spacing of 0.30 m x 0.40 m, in comparison to alternative spacings of 0.40m x 60 cm, 0.60m x 0.80m, and 1.0m x 1.0 m. While yield per individual plant was higher in wider spacing, overall production was maximized in closer spacings due to the increased plant population.

A harvesting height of 30 cm yielded the highest fresh leaf yield during the first harvest, while subsequent harvests documented the highest fresh foliage yield at a harvesting height of 45 cm. More primary branches could be harvested during the first harvest at a height of 30 cm compared to harvesting heights of 45 cm and 60 cm. Since the 30 cm height represented the lower cut, the harvestable area was greater during the first harvest. A larger number of secondary branches emerged after a 45 cm cut on the main stem. As a result, the second harvest produced the highest leaf quantity due to the increased number of secondary branches. Thus, yield was enhanced when harvesting at a height of 45 cm in the second and subsequent harvests. This treatment achieved a fresh leaf yield of 30.25 t/ha, succeeded by a height of 60 cm. The treatment combination of closer spacing in triangle planting at 150 cm x 25cm x 25cm and harvesting at 45 cm (M_3S_2) recorded a higher fresh biomass yield of 42.76 t/ha (Table 3). A comparable trend was noted for dry leaf yield, with this treatment combination yielding 7.83 t/ha .

The fresh-to-dry leaf recovery ratio ranged from 5.23 to 5.79. In order to obtain one kilogram of dry leaves, it is necessary to utilize 5.79 kilograms of fresh leaves.

Influence of agronomic intervention on the micronutrients content in Moringa Leaves

Potassium: The potassium concentration in *Moringa* leaves was significantly elevated (257 mg $100g^{-1}$) when cultivated under a single-row planting arrangement with a wider inter-row spacing of 150 cm x 50 cm (Table 4). The absence of competition due to the wider spacing allows the plants to absorb a greater quantity of nutrients, increasing potassium levels. This enhanced potassium concentration associated with wider spacing corroborates the findings of Basra et al. (16) in *moringa*.

Calcium and Magnesium: In contrast, secondary nutrients such as calcium (3.33%) and magnesium (0.51%) were found at their highest concentrations in a triangular planting configuration with a reduced spacing of 150 cm x 25 cm x 25 cm. These findings substantiate observations made by Basra et al (16) . Furthermore, micronutrients, including zinc (41.53 ppm) and manganese (52.41 ppm), were significantly elevated in double-row planting with narrower spacing of 150 cm x 25 cm x 25 cm (Table 4). Harvesting heights and their interactions did not influence these nutrient levels. Under conditions of closer spacing, plants compete for nutrients, which may lead to an enhanced nutrient assimilation rate. This optimal assimilation of nutrients likely stimulates both metabolic processes and enzymatic activities. Micronutrients serve as precursors for enzymatic activities in the plant body, which may explain the elevated micronutrient content observed with closer spacing. The experimental results corroborate the findings of Ponnuswami and Rani (12) .

Iron: The maximum iron content was recorded at 145 mg per 100g in the broader spatial arrangement of 150 cm x 50 cm. These results may be attributable to elevated chlorophyll levels associated with wider spacing (Table 4). Iron is a crucial element in chlorophyll biosynthesis and the respiration process. These findings align with the research conducted by Ponnuswami and Rani (12) .

Ascorbic acid: The ascorbic acid concentration was significantly elevated, reaching a maximum of 105 mg per 100 g at the broader spacing configuration of 150 cm x 50 cm (Table 4). Ascorbic acid concentration showed a positive correlation with increased spacing. In configurations with wider spacing, the absorption of nutrients was enhanced without competition, thereby augmenting the ascorbic acid content. The broader spatial arrangement facilitated increased chlorophyll synthesis, which, in turn, contributed to the rise in ascorbic acid levels. Similar findings were reported by Kaushal et al. (22) in tomatoes, where a broader plant geometry of 0.75 m x 1.0 m resulted in higher ascorbic acid content compared to the closer spacing of 75 cm x 50 cm. Harvesting heights did not demonstrate a statistically significant effect on ascorbic acid concentration. Comparable results were also documented by Sidhdharth et al. and Basra et al. (2, 16).

Vitamin A: Vitamin A content peaked (18.67 mg 100g^{-1}) with single-row planting at a broader crop geometry of 150 cm x 50 cm (Table 4). Wider spacing enhances light exposure, contributing to higher vitamin A levels by elevating β carotene, the precursor of vitamin A. Harvesting height did not influence vitamin A content across harvests. The 150 cm x 50 cm spacing combination with a 60 cm harvesting height yielded the highest vitamin A content. These results align with (12) in their study on *moringa*.

Crude fiber and crude protein: The current study indicated that crude fiber content was highest (15.32%) at the single-row, broader crop geometry of 150 cm x 50 cm (Table 4). Crude fiber increased as population density decreased with wider spacing. El Morsy documented similar results in *Sesbania* (23) . Harvesting heights and their interaction did not significantly affect crude fiber content.

The highest crude protein content (25.15%) in *moringa* leaves was observed with triangular planting at the narrower intra-row crop geometry of 150 cm x 25 cm x 25cm. This increase is attributed to the elevated population density with closer spacing. These findings are consistent with those of Nandeshwar et al. (18) in chili and El Morsy (23) in *Sesbania*. As noted by Mukangango et al. (24), crude protein content was not influenced by harvesting heights. Additionally, the interaction effect did not influence either crude fiber or crude protein content.

Economic analysis

Economic analysis elucidates the superiority of various crop geometries and harvesting heights. The net income and cost -benefit ratio are maximized with a triangular planting configuration with a plant geometry of 150 cm x 25 cm x 25 cm. Comparable findings were also documented by (25) in their study on fenugreek (26) in their research on rice. The treatment combination of 150 cm x 25 cm x 25 cm spacing, coupled with a harvesting height of 45 cm, yielded the highest net returns (Rs. 418213) and the most favorable benefit-cost ratio (2.87), due to enhanced growth parameters and optimal yield (Table 5).

Table 4. Influence of agronomic interventions on micronutrients and anti-oxidant content in *Moringa* leaves

Treatments	Ca (%)	K (mg/100g)	Fe (ppm)	Zinc (ppm)	Mg (%)	Mn (ppm)	Vitamin C (mg 100g^{-1})	Vitamin A (mg/100g)	Crude fibre (%)	Crude protein(%)
Crop geometry										
M_1 150 cm x 25 cm	3.24	243.66	135.94	36.93	0.46	49.07	90.30	14.20	14.20	24.19
M_2 150 cm x 50 cm	3.14	257.91	145.34	33.64	0.37	45.87	109.55	18.67	15.32	22.99
M_3 150 cm x 25 cm x 25 cm	3.33	238.12	131.84	41.53	0.51	52.41	75.78	9.94	13.44	25.15
M4 150 cm x 50 cm x 50c m	3.23	246.68	137.21	36.09	0.45	48.18	84.24	12.60	14.60	23.79
SEd	0.06	4.92	2.44	2.01	0.02	1.15	7.18	1.86	0.32	0.84
CD (P=0.05)	0.17	9.98	4.97	4.58	0.06	3.29	15.22	4.56	0.85	1.68
Harvesting heights										
S_1 30 cm	3.23	247.01	139.59	36.8	0.45	49.08	88.55	13.23	14.63	24.02
S2 45 cm	3.25	246.62	136.12	37.35	0.44	49.09	89.71	12.56	14.34	24.10
S_3 60 cm	3.23	246.15	137.04	37	0.45	48.57	91.65	15.76	14.21	23.97
SEd	0.06	7.98	4.6	0.61	0.02	1.22	5.61	1.37	0.54	0.58
CD (P=0.05)							NS			
Interaction					NS					

Table 5. Economic analysis of *Moringa* leaf production under High-Density Planting Systems (Total of nine harvests)

Treatment combinations	Fresh leaf yield (kg/ha)	Cost of cultivation (Rs)	Gross income (Rs)	Net income (Rs)	Cost Benefit ratio
M_1S_1	27525	1,83,750	412881	229,131	2.25
M_1S_2	27717	1,83,750	415753	232,003	2.26
M_1S_3	27291	1,83,750	409366	225,616	2.23
M_2S_1	19539	1,54,750	293091	138,341	1.89
M_2S_2	20987	1,54,750	314807	160,057	2.03
M_2S_3	19534	1,54,750	293010	138,260	1.89
M_3S_1	38867	2,23,250	583002	359,752	2.61
M_3S_2	42764	2,23,250	641463	418,213	2.87
M_3S_3	40196	2,23,250	602942	379,692	2.70
M_4S_1	29127	1,85,250	436901	251,651	2.36
M_4S_2	29567	1,85,250	443512	258,262	2.39
M_4S_3	29347	1,85,250	440212	254,962	2.38

Conclusion

Cultivating *Moringa* in a triangular arrangement can effectively maximize leaf biomass yield per unit area through high-density planting. The cultivation of this plant for leaf production is gaining popularity among agricultural practitioners and consumers due to its multiple beneficial properties. Implementing a closer triangular planting spacing of 150 cm x 25 cm x 25 cm, along with a harvesting height of 45 cm, has produced a high fresh leaf biomass yield of 42.76 t/ha, in addition to superior leaf quality. This spacing and harvesting height combination also provides favorable economic returns. Thus, adopting a triangular planting spacing of 150 cm x 25 cm x 25 cm, with a harvesting height of 45 cm, is highly recommended to maximize income and improve the livelihoods of Moringa farmers. Enhanced Moringa leaf biomass production with improved leaf quality-rich in essential vitamins and minerals -will contribute significantly to food security and nutritional stability.

Acknowledgements

The authors thankfully acknowledge the research support provided by the Tamil Nadu Agricultural University, Coimbatore.

Authors' contributions

MPK, RB and MUM conceived the research paper, contributed to the research in the way of layout, design, observations, lab analysis and interpretation concept and wrote the manuscript. GSI and KN performed statistical analysis. GS, CP and MMM gave ideas for designing the tables and graph. MPK, RB and MUM design the tables and graphs. GSI, KN, GS, CP and JD revised and finalized the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used none of AI Technology. The authors reviewed and edited the content as needed and take full responsibility for the publication's content.

References

1. Pandey A, Pradheep K, Gupta R, Roshni Nayar E, Bhandari DC. ‘Drumstick tree’(*Moringa oleifera* Lam.): a multipurpose potential species in India. Genet Resour Crop Evol . 2011;58:453-60. https://doi.org/10.1007/s10722-010-9629-6
2. Sidhdharth G, Nageswari K, Balakumbahan R, Kavitha MP, Uma Maheswari M. Interventions of plant geometry and harvesting heights on growth and leaf yield parameters in Moringa (*Moringa oleifera* Lam.). Madras Agric J. 2022;109(special):155-59.
3. Moyol B, Masika PJ, Hugo A, Muchenje V. Nutritional characterization of Moringa (*Moringa oleifera* Lam.) leaves. Afr J Biotechnol. 2011;10(60):12925-33. https://doi.org/10.5897/AJB10.1599
4. Sreelatha S, Padma PR. Antioxidant activity and total phenolic content of *Moringa oleifera* leaves in two stages of maturity. Plant Foods Hum Nutr. 2009;64:303-11. https://doi.org/10.1007/s11130-009-0141-0
5. Yoshida S, Forno DA, Cock JH, Gomez KA. Laboratory manual for physiological studies of rice. The International Rice Research Institute. 1976.
6. Stanford G, English L. Use of the flame photometer in rapid soil tests for K and Ca.Agron J. 1949(9):446-47. https://doi.org/10.2134/agronj1949.00021962004100090012x
7. Jackson ML. Soil chemical analysis: advanced course: a manual of methods useful for instruction and research in soil chemistry, physical chemistry of soils, soil fertility and soil genesis. UW-Madison Libraries Parallel Press; 2005.
8. Jensen A. Chlorophylls and carotenoids. In: Hellebust JA, Craigie JS.(Eds). Handbook of Phycological Methods, Physiological and Biochemical Methods Cambridge University Press, Cambridge. 1978;59-70.
9. Harris LJ, Ray SN. Diagnosis of vitamin-C sub nutrition by urine analysis with a note on the antiscorbutic value of human milk. Lancet. 1935;228:71-77. https://doi.org/10.1016/S0140-6736(00)57120-7
10. Chemists AoOA, Chemists AoOA. Official methods of analysis of the association of official analytical chemists. Association of Official Analytical Chemists; 1931.
11. Panse VG, Sukhatme PV. Statistical methods for agricultural workers. Indian Council of Agricultural Research.1954.
12. Ponnuswami V, Rani EA. Organic leaf production of Moringa (*Moringa oleifera* Lam.) cv. PKM-1 for higher leaf yield and quality parameters under ultra high density planting system. Adv Plants Agric Res. 2019;9(1):206-14.
13. Bagri S, Singh J, Bhatnagar P, Khatik G, Jain SK, Meena KK. Effect of date of transplanting and crop geometry on growth and physiological attributes of capegooseberry (*Physalis peruviana* L.). Int J Curr Microbiol App Sci. 2018;7(10):3203-06. https://doi.org/10.20546/ijcmas.2018.710.371
14. Maheswari MU, Krishnasamy SM. Effect of crop geometries and plant growth retardants on physiological growth parameters in machine sown cotton. J Pharmacogn Phytochem. 2019;8(2):541-45.
15. Maheswari M, Krishnasamy SM, Kumar M, Sakthive N. Impact of high density planting system and growth retardants on root growth and yield attributes in machine sown cotton. Pharma Innovation. 2019;8(3):123-30.
16. Basra SMA, Nouman W, Rehman HU, Usman M, Nazli Z-e-H. Biomass production and nutritional composition of *Moringa oleifera* under different cutting frequencies and planting spacings. International Journal of Agriculture and Biology. 2015;17(5):1055-060. https://doi.org/10.17957/IJAB/15.0076
17. Bhattarai P, Kaushik RA, Ameta KD, Jain HK, et al. Effect of plant geometry and fertigation on growth and yield of cherry tomato (*Solanum lycopersicon* var. *cerasiforme*) under zero energy polyhouse conditions. Indian J Hortic. 2015;72(2):297-301. https://doi.org/10.5958/0974-0112.2015.00057.2
18. Nandeshwar VN, Bharad S. Effect of planting geometry and fertigation levels on growth, yield and quality of chilli. Journal of Krishi Vigyan. 2019;8(1):63-69. https://doi.org/10.5958/2349-4433.2019.00074.6
19. Teshale M, Tekeste N. Growth and yield response of garlic (L.) to intra-row spacing and variety at selekeleka, Northern Ethiopia. Open Biotechnol J. 2021;15(1)1-11. https://doi.org/10.2174/1874070702115010001

20. Abdullahi S, Maishanu HM, Mukhtar RB. Plant spacing and harvest interval effect on the growth parameters of *Moringa oleifera* Lam. (Periyakulam-1) in Sokoto (semi-arid environment). J Agri Horti Res. 2021;4(3):85-89. https://doi.org/10.33140/JAHR.04.03.01

21. Adegun M, Ayodele O. Growth and yield of *Moringa oleifera* as influenced by spacing and organic manures in South-Western Nigeria. Int J Agron Agric Res. 2015;6(6):30-37.

22. Kaushal S, Sharma V, Singh V. To study the impact of date of transplanting, spacing and training systems on developmental stages and dry matter accumulation in tomato production under protected conditions. J Pharmacogn Phytochem. 2019;8(3):4019-23.

23. El Morsy M. Influence of cutting height and plant spacing on Sesbania (*Sesbania aegyptiaca* [Poir]) productivity under hyper-arid conditions in El-kharga Oasis, El-Wadi El-Gaded, Egypt. Int J Plant Prod. 2009;3(2):77-84. https://doi.org/10.22069/ijpp.2012.643

24. Mukangango M, Nduwamungu J, Naramabuye FX, Nyberg G, Dahlin AS. Biomass production and nutrient content of three agroforestry tree species growing on an acid Anthropic Ferralsol under recurrent harvesting at different cutting heights. Agroforest Syst. 2020;94:857-67. https://doi.org/10.1007/s10457-019-00455-8

25. Meena SS, Meena R, Mehta R, Kakani R. Effect of crop geometry, fertilizer levels and genotypes on growth and yield of fenugreek (*Trigonella foenum-graecum* L.). Legume Res. 2016;39(5):792-96. https://doi.org/10.18805/lr.v0iOF.11247

26. Jaffar Basha S, Basavarajappa R, Babalad H. Crop performance and water use efficiency in aerobic rice (*Oryza sativa* L.) relative to irrigation schedule, planting geometry and method of planting in Northern transition zone of Karnataka, India. Paddy Water Environ. 2017;15:291-98. https://doi.org/10.1007/s10333-016-0548-9