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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

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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 system (HDPS). 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

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

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 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: M1- 150 cm x 25 cm, M2-150 cm x 50 cm, M3-150 cm x 25 cm x 25 cm and M4- 150 cm x 50 cm x 50 cm, alongside three subplot treatments based on different harvesting heights: S1 - 30 cm, S2 - 45 cm, S3 - 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 & 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.

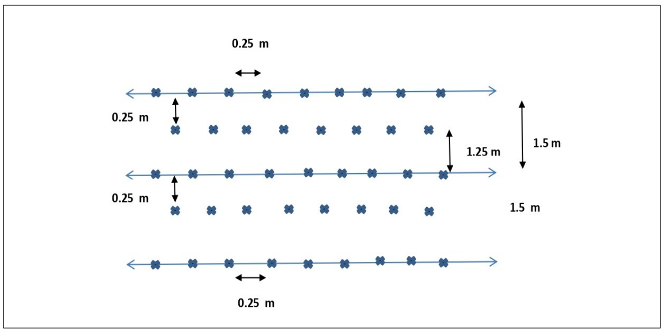

Fig. 1. Double row triangle planting with 150 cm x 25 cm x 25 cm (53,332plants/ha).

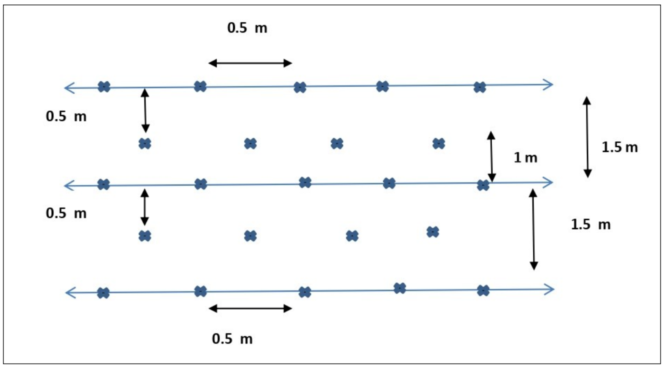

Fig. 2. Double row triangle planting with 150 cm x 50 cm x 50 cm (26,666 plants/ha).

Five tonnes of vermicompost and 45 Kg P_2O_5 (phosphorus pentoxide) were applied as basal doses to enhance the leaf production. To improve biomass yield and fertilizer efficiency, 275 Kg nitrogen and 90 Kg K_2O (potassium oxide) were applied in five splits, repeated in the subsequent year. Biofertilizers, such as Azospirillum, Phosphobacteria and arbuscular mycorrhiza (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 (CGR) and relative growth rate.

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

$$\text{Light Interception (\%)} = \frac{\text{Light intensity in open (Lux) - Average intensity in crop (Lux)}}{\text{Light intensity in open (Lux)}} \quad ..\text{(Eqn. 1)}$$

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

$$\text{Total chlorophyll} = \frac{\text{OD at 652 nm} \times V}{34.5 \times W} \quad ..\text{(Eqn. 2)}$$

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 standard procedure (6). Iron and zinc content in the leaf samples were estimated using an atomic absorption spectrophotometer following a standardized protocol (6). Manganese content was estimated using an Atomic absorption spectrophotometer following a standardized protocol (7). Calcium and Magnesium were estimated by titration with a standardized EDTA (ethylene diamine tetraacetic acid) solution.

The amount of vitamin A and ascorbic acid in leaf samples was quantified following standardized procedures (8, 9). The amount of crude fiber was estimated by the muslin cloth method (10). Crude protein was estimated using the following formula:

$$\text{Crude protein (\%)} = \text{Nitrogen (\%)} \times 6.25 \quad ..... \text{(Eqn. 3)}$$

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 (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**	
SE	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 in a study (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 also reported in cotton (14).

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 results align with a previous investigation (15).

Crop growth rate (CGR): CGR refers to the change in dry weight in a certain time span. The highest CGR of 6.80g /m^2/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.) The results support the conclusions of previous studies on cotton and moringa (14, 16). The influence of subplot treatment had a significant impact on CGR.

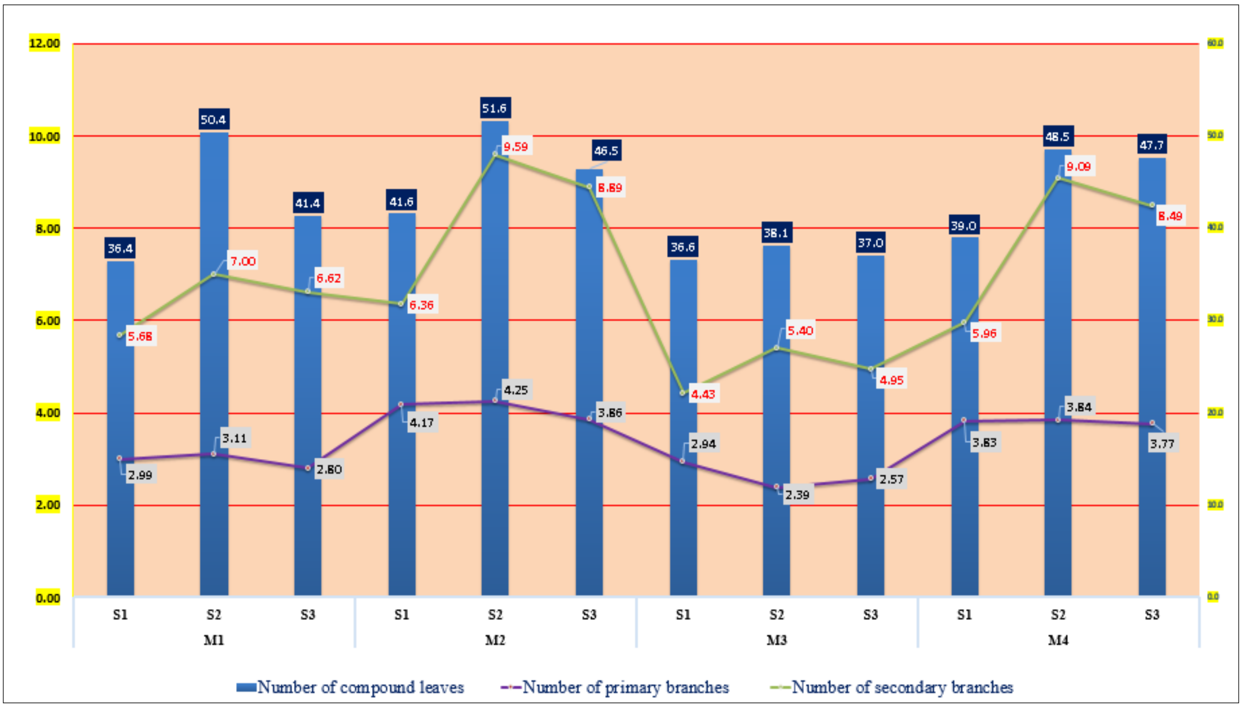

Fig. 3. Influence of crop geometry and harvesting height on growth characteristics of moringa under HDPS.

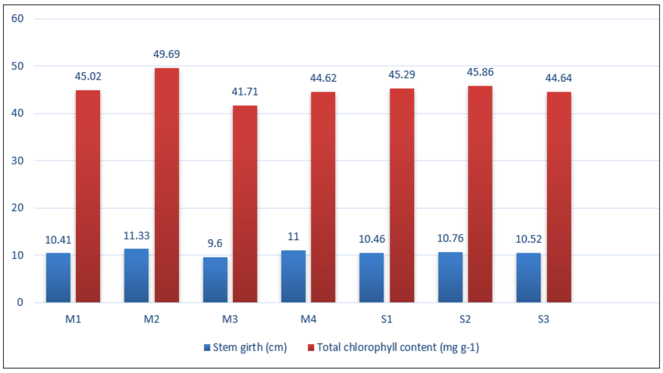

Fig. 4. Influence of crop geometry and harvesting height on stem girth (cm) and total chlorophyll content (mg g^{-1}) of moringa under HDPS.

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 CGR 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. Comparable outcomes were also observed in cherry tomato (17), cape gooseberry (13), chilli (18) and garlic (19). 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 (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 harvesting height of 45 cm, amounting to 30.25 t. Denser spacing allows for more plants, while wider spacing

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	
SE	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 (cm^2)					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	
SE	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	
SE	0.530	0.95	1.90	2.11	
CD (p= 0.05)	1.298	2.01	4.03	4.61	
	Dry leaf yield (tonnes/ha)				
Treatments	**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	
SE	0.10	0.18	0.36	0.40	
CD (p= 0.05)	0.25	0.39	0.76	0.88	

accommodates fewer. A denser layout enhances plant population, hence improving production in such arrangements. These results align with the findings of previous studies (16, 20). It was also reported from a previous report that moringa biomass output was highest at the denser spacing of 0.30 m x 0.40 m, in comparison to alternative spacings of 0.40 m x 60 cm, 0.60 m x 0.80 m and 1.0 m x 1.0 m (21). 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 25 cm x 25 cm and harvesting at 45 cm (M3S2) 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 with the outcome of a study on moringa (16).

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 the findings of a previous investigation (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 with a previous finding (12).

Iron: The maximum iron content was recorded at 145 mg per 100 g 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 configuration enhanced chlorophyll production, subsequently leading to elevated ascorbic acid levels, consistent with a previous study (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. The harvesting heights did not exhibit a statistically significant impact on ascorbic acid concentration, aligning with the findings of earlier investigations (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 × 50 cm spacing configuration with a 60 cm harvesting height produced the maximum vitamin A content, consistent with findings from a study on moringa (12).

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. Similar results were also documented 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 align with the results of studies on chilli (18) and Sesbania (23). Furthermore, the crude protein content remained unaffected by the harvesting heights (24). 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 in fenugreek (25) and rice (26). 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	Calcium (%)	Potassium (mg/100g)	Iron (ppm)	Zinc (ppm)	Magnesium (%)	Manganese (ppm)	Vitamin C (mg $100g^{-1}$)	Vitamin A (mg/100g)	Crude fibre (%)	Crude protein (%)
Crop geometry										
M1 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
M2 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
M3 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
SE	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										
S1 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
S3 60 cm	3.23	246.15	137.04	37	0.45	48.57	91.65	15.76	14.21	23.97
SE	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 HDPS (Total of nine harvests)

Treatment combinations	Fresh leaf yield (Kg/ha)	Cost of cultivation (Rs)	Gross income (Rs)	Net income (Rs)	Cost benefit ratio
M1S1	27525	1,83,750	412881	229,131	2.25
M1S2	27717	1,83,750	415753	232,003	2.26
M1S3	27291	1,83,750	409366	225,616	2.23
M2S1	19539	1,54,750	293091	138,341	1.89
M2S2	20987	1,54,750	314807	160,057	2.03
M2S3	19534	1,54,750	293010	138,260	1.89
M3S1	38867	2,23,250	583002	359,752	2.61
M3S2	42764	2,23,250	641463	418,213	2.87
M3S3	40196	2,23,250	602942	379,692	2.70
M4S1	29127	1,85,250	436901	251,651	2.36
M4S2	29567	1,85,250	443512	258,262	2.39
M4S3	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.

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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. GS[1] and KN performed statistical analysis. GS[2], CP and MMM gave ideas for designing the tables and graph. MPK, RB and MUM designed the tables and graphs. GS[1], KN, GS[2], CP and JD revised and finalized the manuscript. All authors read and approved the final manuscript. (GS[1] stands for G Sidhdharth and GS[2] for G Sudhakar)

Compliance with ethical standards

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

Ethical issues: None

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