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EFFECT OF BIOCHAR AND NPK MANAGEMENT ON GROWTH AND YIELD OF MORINGA (*Moringa oleifera*)

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Abstract

A field experiment was conducted at Ukhiya, Cox's Bazar, Bangladesh, during 2022-2024 to evaluate the performance of *Moringa oleifera* var. PKM-2 under different bamboo biochar and NPK fertilizer treatments. The experiment was laid out in a randomized complete block design with three replications, consisting of four biochar doses (0, 5, 10, and 15 t ha^{-1}) and four NPK fertilizer levels (0, 50, 100, and 150% of the recommended fertilizer dose, RFD), resulting in 16 treatment combinations. Results revealed that both biochar and NPK significantly improved plant growth and yield attributes. Application of 10-15 t ha^{-1} biochar enhanced plant height, crown spread, pod number, pod length and 1000-seed weight compared to the control. Fertilizer application at 100-150% RFD increased vegetative growth, pod development, and seed yield. Among the interactions, 10 t ha^{-1} biochar with 100% RFD produced the highest pod number (90 $plant^{-1}$) and longest pods (55.69 cm), while 10 t ha^{-1} biochar with 150% RFD resulted in the tallest plants (3.95 m at 24 months). The heaviest seeds (140.54 g per 1000 grains) were recorded with 15 t ha^{-1} biochar. These findings suggest that 10 t ha^{-1} bamboo biochar combined with 100-150% RFD is optimal for maximizing moringa productivity under coastal agro-ecological conditions of Cox's Bazar.

Introduction

Moringa (*Moringa oleifera* Lam.) is a fast-growing, drought-tolerant tree, valued for leaf, pod and seed uses in food, feed and nutraceuticals. Its leaves and pods supply dense proteins, vitamins and minerals (notably Ca, K, Fe and provitamin A), making it a strategic crop for household nutrition and climate-resilient farming across South Asia (Moyo *et al.*, 2011; Gopalakrishnan *et al.*, 2016; Sultana, 2020 and Pareek *et al.*, 2023). In Bangladesh, interest in moringa is rising as farmers diversify beyond rice and seek year-round, nutrient-rich produce under erratic rainfall and heat stress. The crop's ability to thrive on relatively poor soils, coupled with high nutritional returns per unit area, underpins its appeal for coastal smallholders.

Coastal agro-ecosystems, including Cox's Bazar, face soil constraints that can limit perennial tree-crop performance: coarse textures with low organic matter and nutrient stocks, and seasonal salinity pulses from tidal flooding and saltwater intrusion. Empirical work from Jhilwanja Union (Cox's Bazar) reports sandy to loam textures, very low organic matter and N, and low-to-moderate soil electrical conductivity, highlighting the need for amendments that build carbon, water retention, and cation exchange capacity (Hossain *et al.*, 2015). At a broader scale, projections indicate substantial salinity intensification across coastal Bangladesh by mid-century, with implications for crop productivity without adaptive soil management (Dasgupta *et al.*, 2015).

Biochar, a carbon-rich, porous material from biomass pyrolysis, has emerged as a practical soil amendment to address exactly these constraints by improving soil structure, water-holding, pH buffering, and nutrient retention. Field meta-analyses showed that biochar can raise yields particularly in tropical, low-fertility soils (Jeffery *et al.*, 2017) and that pairing biochar with mineral fertilizers enhances crop response and nutrient-use efficiency (Faloye *et al.*, 2017; Ye *et al.*, 2020). Bamboo-derived biochar is especially attractive in South Asia due to abundant feedstock and favorable physicochemical properties; recent studies document improvements in soil water retention, pH moderation and microbial activity with bamboo biochar additions (Yadav and Bag, 2023; Zhang *et al.*, 2024). Complementarily, judicious NPK fertilization is known to boost moringa growth and yield traits (Atteya *et al.*, 2021). Against this backdrop, the present study evaluates how different rates of bamboo biochar and NPK, influence moringa growth and yield, separately and in combination under coastal soil conditions typical of Cox's Bazar.

Materials and Methods

The field experiment was conducted during 2022-2024 at Ukhiya, Cox's Bazar, Bangladesh. The test crop was *Moringa oleifera* (var. PKM-2). Seeds were collected from a reliable local source, soaked in water for 24 h, pre-germinated in gunny bags for 48 h, and then sown in a nursery bed on 8 April 2022. Thirty-day-old seedlings were transplanted into the main field on 4 May 2022 at a spacing of 2.5 m × 2.5 m.

The experiment was laid out in a randomized complete block design (RCBD) with two factors and three replications. Factor A was biochar dose, with four levels: A_0 = 0 t ha^{-1}(control), A_1 = 5 t ha^{-1}, A_2 = 10 t ha^{-1}, and A_3 = 15 t ha^{-1}. Factor B was NPK fertilizer dose, with four levels: B_0 = 0% of recommended fertilizer dose (RFD), B_1 = 50% RFD, B_2 = 100% RFD, and B_3 = 150% RFD. This resulted in 16 treatment combinations: A_0B_0, A_0B_1, A_0B_2, A_0B_3; A_1B_0, A_1B_1, A_1B_2, A_1B_3; A_2B_0, A_2B_1, A_2B_2, A_2B_3; A_3B_0, A_3B_1, A_3B_2, and A_3B_3.

Land was prepared with a power tiller on 17 April 2022, sun-dried for one week, then harrowed and cross-ploughed. Bamboo biochar was incorporated into the soil as pre-treatment. NPK fertilizers were applied using urea (N), TSP (P), and MoP (K) to supply target nutrient levels of 150 kg N, 50 kg P and 75 kg K ha^{-1}, adjusted to the treatment levels (0-150% of RFD). The unit plot size was 2.0 m × 2.0 m with 1.5 m spacing between blocks and 1.0 m between plots to reduce border effects.

Irrigation and drainage were managed according to seasonal conditions, with drainage channels maintained during the rainy season. Manual weeding was performed at approximately 30 and 60 days after transplanting (DAT). Pest monitoring was done regularly, but no insecticides were applied. Plants were harvested at physiological maturity when 80-90% of pods had matured. Pods were collected from the central 1 m area of each plot, dried and weighed. Seeds were dried to 14% moisture content before weighing. Five plants per plot were randomly selected for detailed observations.

The data recorded included plant height (m) at 6, 12, 18, and 24 months; crown spread (m); stem girth (cm at 15 cm height); number of leaves plant^{-1}; fresh leaf weight (g plant^{-1}); number of pods plant^{-1}; pod length (cm, average of five pods); fresh pod weight (g plant^{-1}); and 1000-seed weight (g). Data were subjected to analysis of variance (ANOVA) following the RCBD two-factor design. Mean separation was carried out using the least significant difference (LSD) test at the 5% level of probability.

Results and Discussion

Effect of biochar doses

Relative to A_0, biochar enhanced vegetative growth and reproductive traits throughout 6-24 months (Tables 1-4). By 24 months, plant height rose from 3.36 m (A_0) to 3.69 m (A_2) and 3.67 m (A_3) (Table 1); canopy size increased from 318 to ~387-389 leaves plant^{-1} under A_2-A_3, with leaf mass rising from 132.14 g (A_0) to 180.68 g (A_2) (Table 2). Reproductive gains followed: pods plant$^{-º}$ increased from 62.08 (A_0) to 73.75 (A_2) and 72.25 (A_3), and pod length from 48.57 cm (A_0) to ~50-51 cm (A_2-A_3) (Table 3). Seed traits improved, with 1000-seed weight moving from 121.99 g (A_0) to 140.54 g (A_3) (Table 4).

Table 1. Effect of biochar, NPK doses and their interaction on plant height of Moringa

Treatments	Plant height (m) at			
	6 Months	12 Months	18 Months	24 Months
Biochar effect				
A_0	1.26 b	2.02 b	2.70 c	3.36 b
A_1	1.52 a	2.31 a	2.92 b	3.64 a
A_2	1.56 a	2.32 a	3.03 a	3.69 a
A_3	1.36 b	2.26 a	3.09 a	3.67 a
CV (%)	11.9 6	5.72	2.91	4.83
SE (±)	0.05	0.04	0.02	0.05
NPK effect				
B_0	1.32 b	2.02c	2.67 d	3.45 b
B_1	1.42 ab	2.20b	2.87 c	3.52 b
B_2	1.49 a	2.38a	3.05 b	3.58 b
B_3	1.46 ab	2.31a	3.15 a	3.82 a
CV (%)	11.96	5.72	2.91	4.83
SE (±)	0.05	0.04	0.02	0.05
Interaction effect				
A_0B_0	1.12 cd	1.65 g	2.28 j	3.14 d
A_0B_1	1.41 bc	1.987 f	2.72 hi	3.34 cd
A_0B_2	1.02d	1.98 f	2.79 gh	3.35 cd
A_0B_3	1.49 b	2.46 b	2.99 cdef	3.61 bc
A_1B_0	1.36 bc	2.14 def	2.63 i	3.61 bc
A_1B_1	1.52 b	2.17 def	2.86 fgh	3.57 bc
A_1B_2	1.52b	2.497 b	3.07 bcde	3.53 bc
A_1B_3	1.66 ab	2.42 bc	3.13 bcd	3.86 ab
A_2B_0	1.41 bc	2.08 ef	2.85 fgh	3.48 c
A_2B_1	1.39 bc	2.35 bcd	2.93 efg	3.49 c
A_2B_2	1.88 a	2.83 a	3.20 ab	3.84 ab
A_2B_3	1.54 b	2.02 f	3.15 bc	3.95 a
A_3B_0	1.39 bc	2.20 cdef	2.91 efg	3.57 bc
A_3B_1	1.36 7bc	2.3 bcde	2.98 def	3.67 abc
A_3B_2	1.53 b	2.21 cdef	3.14 bc	3.58 bc
A_3B_3	1.13 cd	2.33 bcd	3.34 a	3.85 ab
CV (%)	12.1	5.72	2.91	4.83
SE (±)	0.03	0.07	0.05	0.01

In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly at 0.05 level of probability. (A_0:0 t ha^{-1}, A_1: 5 t ha^{-1}, A_2: 10 t ha^{-1}, A_3: 15 t $ha^{-1}$and B_0:0% of RFD, B_1: 50% of RFD, B_2: 100% of RFD, B_3: 150% of RFD).

These outcomes agree with evidence that biochar improves soil moisture retention, cation-exchange capacity, pH buffering and nutrient availability, thereby supporting larger canopies and stronger sink formation (Jeffery *et al*., 2017; Ye *et al*., 2020). Mechanistically, biochar can stabilize macro-aggregates and curb N losses, which reinforces sustained biomass and pod/seed filling over multiple seasons (Khan *et al*., 2023; Han *et al*., 2023).

Table 2. Effect of biochar, NPK doses and their interaction on number of leaves plant^{-1} and weight of leaves of *Moringa*

Treatments	Number of leaves plant^{-1} at				Weight of leaves (g) at			
	6 Months	12 Months	18 Months	24 months	6 Months	12 Months	18 Months	24 Months
Biochar effect								
A_0	33.42 c	127.08c	227.42 c	318 c	28.82 b	120.01 c	129.92 c	132.14 c
A_1	55.25 a	152.83 ab	241.25 b	351 b	35.20 a	148.61 b	161.83 b	166.83 b
A_2	53.58 a	149.00 b	253.50 a	387 a	35.32 a	166.62 a	181.26 a	180.68 a
A_3	46.50 b	153.08 a	252.42 a	389 a	27.38 c	149.91 b	164.50 b	165.20 b
CV (%)	5.96	3.19	2.58	2.56	5.96	3.19	3	2.5
SE (±)	0.81	1.34	1.82	1.89	0.81	1.34	2.11	1.92
NPK effect								
B_0	34.50 d	130.50 d	223.92 c	316c	29.09 c	127.57 c	138.56 c	140.36 c
B_1	51.42 b	140.08 c	236.83 b	337b	32.06 b	148.84 b	161.67 b	163.75 b
B_2	48.50 c	153.50 b	254.42 a	391a	31.11 b	148.19 b	160.73 b	161.69 b
B_3	54.33 a	157.92 a	259.42 a	412a	34.46 a	160.55 a	176.56 a	179.04 a
CV (%)	5.89	3.05	2.12	2.07	4.56	2.74	4.3	4.86
SE (±)	0.89	1.89	1.78	1.56	0.42	1.16	1.98	2.26
Interaction effect								
A_0B_0	32.00 g	117.00 h	207.67 j	296.67 h	30.81 d	117.93 g	128.44 ef	108.01 j
A_0B_1	27.67 gh	107.00 i	221.00 h	313.67 g	25.18 e	110.54 h	116.86 f	122.73 hi
A_0B_2	24.00 h	137.00 fg	233.33 fgh	324.33 fg	21.97 f	109.27 h	117.73 f	124.61 ghi
A_0B_3	50.00 e	147.33 de	247.67 cde	342.67 cd	37.32 bc	142.28 e	156.65 d	132.60 def
A_1B_0	40.33 f	130.00 g	222.67 gh	317.33 fg	31.56 d	119.05 g	128.43 ef	120.62 i
A_1B_1	66.67 ab	159.67 abc	235.00 efg	329.00 ef	35.81 c	156.86 c	172.12 bc	125.85 f-i
A_1B_2	54.33 de	166.67 a	247.00 c-f	343.33 cd	36.67 c	153.54 cd	166.87 cd	134.48 de
A_1B_3	59.67 c	155.00 bcd	260.33 bc	355.33 bc	36.76 c	164.97 b	179.92 b	139.67 cd
A_2B_0	26.00h	136.33 fg	230.33 gh	318.67 fg	22.34 f	129.74 f	139.52 e	122.82 hi
A_2B_1	52.33 e	144.67 ef	244.67 def	329.67 ef	37.60 bc	170.18 b	183.29 b	130.90 efg
A_2B_2	71.33 a	152.67 cde	279.33 a	370.00 a	41.52 a	183.36 a	195.65 a	152.24 a
A_2B_3	64.67 b	162.33 ab	259.67 bc	360.00 ab	39.84 ab	183.20 a	206.59 a	131.71 efg
A_3B_0	39.67 f	138.67 f	235.00 efg	320.33 fg	31.65 d	143.56 e	157.84 d	128.49 e-h
A_3B_1	59.00 cd	149.00 de	246.67 c-f	338.00 de	29.64 d	157.77 c	174.42 bc	139.60 cd
A_3B_2	44.33 f	157.67 bc	258.00 bcd	351.00 bcd	24.29 ef	146.58 de	162.66 cd	144.50 bc
A_3B_3	43.00f	167.00 a	270.00 ab	368.33 a	23.93 ef	151.74 cd	163.10 cd	149.55 ab
CV (%)	5.96	3.19	2.58	2.16	4.56	2.74	4.29	3.16
SE (±)	1.62	2.68	3.64	4.21	0.83	2.32	3.95	2.4

In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly at 0.05 level of probability. (A_0: 0 t ha^{-1}, A_1: 5 t ha^{-1}, A_2: 10 t ha^{-1}, A_3: 15 t ha^{-1} and B_0: 0% of RFD, B_1: 50% of RFD, B_2: 100% of RFD, B_3: 150% of RFD).

Effect of NPK doses

Increasing fertilizer from B_0 to B_3 steadily raised plant stature and canopy size and improved pod traits (Tables 1-3): at 24 months, height rose from 3.45 m (B_0) to 3.82 m (B_3) (Table 1), leaves plant^{-1} from 316 (B_0) to 412 (B_3), and leaf mass from 140.36 g (B_0) to 179.04 g (B_3) (Table 2). Pods plant^{-1} climbed from 56.42 (B_0) to 78.67 (B_3), while pod length rose from 46.23 cm (B_0) to 51.79 cm (B_3) (Table 3). For yield components, diminishing returns appeared at the highest dose: at 24 months pod weight peaked at B_1-B_2 (182.63-182.49 g) rather than B_3 (176.09 g) and 1000-seed weight plateaued at B_2-B_3 (~139 g) (Table 4).

Table 3. Effect of biochar, NPK doses, and their interaction on number of pods plant^{-1} and length of pods of moringa

Treatments	Number of pods plant^{-1} at				Length of pods (cm) at			
	6 Months	12 Months	18 Months	24 Months	6 Months	12 Months	18 Months	24 Months
Biochar effect								
A_0	1.25 c	16.50 d	42.50 c	62.08 c	2.79 c	25.54 d	36.47 c	48.57 c
A_1	2.25 b	19.92 c	46.75 b	66.58 b	2.33 c	27.41 c	38.12 b	49.98 b
A_2	3.25 a	21.17 b	46.42 b	73.75 a	3.65 b	29.13 b	39.41 a	51.38 a
A_3	2.83 a	22.33 a	49.17 a	72.25 a	4.49 a	30.12 a	40.34 a	50.70 ab
CV (%)	21.04	5.48	2.75	4.17	10.54	2.32	3.06	2.74
SE (±)	0.15	0.32	0.37	0.83	0.1	0.19	0.34	0.4
NPK effect								
B_0	1.25 c	14.17 d	38.08 c	56.42 c	2.55 c	24.30 d	35.20 d	46.23 c
B_1	2.25 b	18.33 c	44.58 b	63.83 c	2.24 d	26.97 c	37.51 c	49.83 b
B_2	2.58 b	22.08 b	50.83 a	75.75 b	4.06 b	29.52 b	39.82 b	52.79 a
B_3	3.50 a	25.33 a	51.33 a	78.67 a	4.40 a	31.42 a	41.81 a	51.79 a
CV (%)	21.04	5.48	2.75	4.17	10.54	2.32	3.06	2.74
SE (±)	0.15	0.32	0.37	0.83	0.1	0.19	0.34	0.4
Interaction effect								
A_0B_0	2.00 d	12.00 i	34.33 g	53.00 k	5.06 b	22.18 g	33.35 i	45.00 d
A_0B_1	0.00 f	16.00 g	39.67 f	59.33 ij	0.00 f	24.66 f	35.88 h	47.37 d
A_0B_2	1.00 e	18.00 f	46.33 d	65.67 gh	4.05 c	26.58 e	37.31 fgh	50.12 c
A_0B_3	2.00 d	20.00 e	49.67 bc	70.33 efg	2.06 e	28.73 d	39.35 def	51.81 bc
A_1B_0	0.00 f	14.00 h	36.33 g	55.00 jk	0.00 f	24.13 f	35.35 h	45.53 d
A_1B_1	2.00 d	18.00 f	44.00 e	61.67 hi	2.08 e	26.03 e	36.13 gh	49.69 c
A_1B_2	3.00 c	22.33 d	50.67 b	72.00 ef	3.00 d	29.18 d	39.50 cde	52.02 bc
A_1B_3	4.00 b	25.33 bc	56.00 a	77.67 cd	4.22 c	30.30 c	41.51 bcd	52.68 b
A_2B_0	1.00 e	15.00 gh	39.33 f	57.67 ijk	1.98 e	24.82 f	35.95 h	47.05 d
A_2B_1	3.00 c	19.00 ef	47.00 d	66.33 gh	3.12 d	28.38 d	38.18 efg	50.05 c
A_2B_2	4.00 b	23.67 cd	51.33 b	90.00 a	4.21 c	30.60 c	40.83 bcd	55.69 a
A_2B_3	5.00 a	27.00 b	48.00 cd	81.00 bc	5.28 b	32.72 b	42.68 ab	52.73 b
A_3B_0	2.00 d	15.67 gh	42.33 e	60.00 ij	3.15 d	26.05 e	36.13 gh	47.35 d
A_3B_1	4.00 b	20.33 e	47.67 cd	68.00 fg	3.77 c	28.80 d	39.87 cde	52.21 bc
A_3B_2	2.33 cd	24.33 c	55.00 a	75.33 de	4.99 b	31.71 b	41.66 abc	53.32 b
A_3B_3	3.00 c	29.00 a	51.67 b	85.67 ab	6.03 a	33.92 a	43.70 a	49.92 c
CV (%)	21.04	5.48	2.75	4.17	10.54	2.32	3.06	2.74
SE (±)	0.29	0.63	0.73	1.65	0.2	0.37	0.68	0.79

In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly at 0.05 level of probability. (A_0: 0 t ha^{-1}, A_1: 5 t ha^{-1}, A_2: 10 t ha^{-1}, A_3: 15 t ha^{-1} and B_0:0% of RFD, B_1: 50% of RFD, B_2: 100% of RFD, B_3: 150% of RFD).

This pattern matches moringa studies where balanced N and P boost leaf growth and tissue nutrition, while adequate K underpins pod elongation, assimilate transport, and seed filling; excessive N can shift partitioning toward foliage at the expense of seed mass (Kumar *et al*., 2006; Atteya *et al*., 2021).

Interaction of biochar and NPK

Co-application produced the strongest outcomes, with $A_2 \times (B_2\text{-}B_3)$ and $A_3 \times B_3$ repeatedly leading (Tables 1-4). For height, A_2B_3 achieved the overall maximum of 3.95 m at 24 months (Table 1). Pod set and pod length peaked at A_2B_2 (90 pods plant^{-1}; 55.69 cm), with A_3B_3 and A_1B_3 also high across stages (Table 3). Vegetative yield was likewise strongest under A_2B_2/A_2B_3 and A_3B_3 (Table 2). An interesting exception is the very high pod weight at 24 months under A_0B_1 (204.99 g) (Table 4), plausibly reflecting a source-sink compensation: with fewer pods and a lighter canopy, assimilates can be preferentially allocated to each pod, increasing unit mass (Baïram *et al.*, 2019).

Table 4. Effect of biochar, NPK doses, and their interaction on pod weight and 1000-seed weight of Moringa

Treatments	Weight of pods (g) at				1000 seeds weight (g)
	6 Months	12 Months	18 Months	24 Months	
Biochar effect					
A_0	10.72 d	120.64 c	139.45 c	177.47 b	121.99 d
A_1	15.64 c	128.43 b	148.22 b	172.87 c	130.16 c
A_2	22.93 b	131.49 a	155.01 a	182.52 a	134.42 b
A_3	26.92 a	128.36 b	149.14 b	177.55 b	140.54 a
CV (%)	9.95	1.91	1.73	1.61	3.16
SE (±)	0.55	0.7	0.74	0.83	1.2
NPK effect					
B_0	11.67 d	121.04 d	142.43 b	169.19 c	119.98 c
B_1	15.18 c	123.56 c	143.01 b	182.63 a	129.77 b
B_2	21.96 b	133.34 a	153.73 a	182.49 a	138.96 a
B_3	27.39 a	130.98 b	152.66 a	176.09 b	138.38 a
CV (%)	9.95	1.91	1.73	1.61	3.16
SE (±)	0.55	0.7	0.74	0.83	1.2
Interaction effect					
A_0B_0	12.91 gh	115.32 i	137.04 f	166.07 hi	108.01 j
A_0B_1	0.00 i	108.40 j	121.26 g	204.99 a	122.73 hi
A_0B_2	12.22 h	127.42 ef	147.59 de	172.74 fg	124.61 ghi
A_0B_3	17.73 ef	131.43 de	151.92 cd	166.08 hi	132.60 def
A_1B_0	0.00 i	120.39 h	139.81 f	164.02 i	120.62 i
A_1B_1	15.83 fg	125.89 fg	144.91 e	171.25 fg	125.85 f-i
A_1B_2	20.88 de	131.39 de	150.52 cd	174.65 efg	134.48 de
A_1B_3	25.85 c	136.04 bc	157.64 b	181.56 cd	139.67 cd
A_2B_0	15.38 fgh	122.54 gh	147.41 de	171.56 fg	122.82 hi
A_2B_1	20.98 de	127.19 ef	153.78 bc	176.00 ef	130.90 efg
A_2B_2	25.02 c	135.06 cd	154.12 bc	196.04 b	152.24 a
A_2B_3	30.33 b	141.16 a	164.74 a	186.46 c	131.71 efg
A_3B_0	18.39 ef	125.89 fg	145.46 e	175.13 efg	128.49 e-h
A_3B_1	23.91 cd	132.77 cd	152.11 cd	178.27 de	139.60 cd
A_3B_2	29.72 b	139.50 ab	162.68 a	186.53 c	144.50 bc
A_3B_3	35.67 a	115.28 i	136.31 f	170.26 gh	149.55 ab
CV (%)	9.95	1.91	1.73	1.61	3.16
SE (±)	1.09	1.4	1.47	1.65	2.41

In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly at 0.05 level of probability. (A_0: 0 t ha^{-1}, A_1: 5 t ha^{-1}, A_2: 10 t ha^{-1}, A_3: 15 t ha^{-1} and B_0:0% of RFD, B_1: 50% of RFD, B_2: 100% of RFD, B_3: 150% of RFD).

Overall, these patterns fit the well-documented synergy where biochar improves fertilizer-use efficiency, P availability and moisture buffering, delivering yield advantages beyond fertilizer alone across seasons (Ye *et al.*, 2020; Faloye *et al.*, 2017). Practically, targeting A_2 with B_2-B_3

(≈10 t ha^{-1} biochar plus 100-150% RFD) appears optimal for maximizing combined growth, pod set and seed traits under comparable conditions.

Conclusion

Across 6-24 months, both biochar and NPK fertilizer substantially improved moringa growth and yield. Relative to no biochar and no fertilizer, applying 10-15 t ha^{-1} biochar together with 100-150% of the recommended fertilizer dose increased plant height, canopy size, leaf mass, pods per plant, pod length, pod weight and 1000-seed weight. The best overall performance occurred around 10 t ha^{-1} biochar combined with the recommended-supra fertilizer range: 10 t ha^{-1} + 150% RFD produced the tallest plants at 24 months (3.95 m), while 10 t ha^{-1} + 100% RFD gave the highest pod number (90) and the longest pods (55.69 cm). Vegetative traits (leaf number and leaf weight) were likewise strongest under 10-15 t ha^{-1} with 100-150% RFD. Seed size peaked with 15 t ha^{-1} biochar (1000-seed weight 140.54 g) and plateaued near 100-150% RFD (~139 g). One notable exception was a very high pod weight under 0 t ha^{-1} biochar with 50% RFD (204.99 g), likely reflecting source-sink compensation rather than superior overall productivity. For similar environments, a practical recommendation is ~10 t ha^{-1} biochar with 100-150% of the recommended NPK dose to maximize combined vegetative and reproductive performance. As this trial covered a single site-year within one AEZ, multi-year evaluations across additional AEZs are advised before broad-scale recommendation.

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