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Productivity and nutritional aspects in *Moringa oleifera* plants fertilized with NPK in south-eastern Brazil

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Moringa (*Moringa oleifera* Lam.) belonging to family Moringaceae is originating from the foothills of the Himalayan mountain range that presentes rapid growth and good development in tropical and subtropical climates (Yadav *et al.* 2022). Its species are being cultivated for thousands of years for its nutritional and pharmacological properties such as human nutrition, treatment of illnesses, industrial and fuel use, animal feed, and water purification (Gandji *et al.* 2018, Yadav *et al.* 2024). Nutritional and phytochemical attributes, and medicinal properties of moringa have been widely studied by the global scientific community (Kaur and Sontakke 2023, Yadav *et al.* 2023) but research aimed at investigating cultural and agronomic aspects, including adequate nutritional supply, is still incipiente. Fertilization management directly impacts the productivity and quality of cultivated plants, which makes it essential to determine adequate doses of nutrients to improve their yields and increase fertilizer use efficiency (Salim and Raza 2020).

Knowing the productivity and nutritional aspects of moringa plants in response to nitrogen (N), phosphorus (P) and potassium (K) fertilization helps to improve fertilization recommendations and subsidize the expansion of cultivation areas, ensuring good levels of productivity and economic return to producers. Thus, this study aimed to determine NPK doses for moringa, as well as critical levels of N, P and K in the shoot of plants.

The experiment was conducted during 2021 and 2022 at Federal Institute of Minas Gerais (18°33′10″ S and 42°45′12″ W, with 713 m of altitude), São João Evangelista-MG, Doce River Valley, South-Eastern Brazil. The site is in the Atlantic Forest Biome and has a subtropical climate with dry winters, with average annual temperature and precipitation 21.2°C and 1,000 mm, respectively. Experimental soil is a Oxisol, with clayey texture, *p*H of 5.09, low organic matter content (1.91%), low P availability (5.11 mg/dm^3) and high potassium availability (144.0 mg/dm^3). Soil acidity was corrected with dolomitic limestone (effective neutralizing value of 85%) incorporated to a depth of 0.20 m to increase base saturation to 50%. Planting holes (30 cm × 30 cm × 30 cm) were manually opened and the seedlings were established at a spacing of 1.0 m between rows and 0.6 m between plants (16,666 plants/hectare), in a non-irrigated cultivation system.

The experimental design was a fractional factorial of the type $(1/2)4^3$, with 32 treatments set up in four blocks, as proposed by Conagin *et al.* (1997). The treatments represented combinations of 4 doses of N (0, 40, 80 and 160 kg/ha) applied as urea (44% N); 4 doses of P_2O_5 (0, 45, 90 and 180 kg/ha) applied as triple superphosphate (41% P_2O_5); and 4 doses of K_2O (0, 20, 40 and 80 kg/ha) applied as potassium chloride (52% K_2O). P_2O_5 doses were fully applied at the time of planting. The experimental area also received 4.0 kg/ha of Zn (zinc sulfate 20% Zn) and 1.0 kg/ha of B (boric acid 17% B) fertilizations with N, K_2O, B and Zn were repeated in the second year of cultivation.

Each experimental unit was composed of four seedlings arranged in a row (seeds coming from a seed collection area located in Birigui-SP, Brazil). Plant shoot harvests were carried out every 60 days (January, March, May, July, September and November) for two consecutive years (2021 and 2022). The shoot fresh matter was determined at each harvest, followed by packaging in paper bags and drying in an oven at 65°C until constant weight to determine dry matter. Composite samples of the shoot dry matter of the plants were prepared each year to determine N, P, and K contents (Silva 2009). The N, P, and K content accumulated in the shoot was calculated by multiplying the content in the samples by the dry matter harvested in the year. The data were grouped into three periods to carry out the analyses: Year 1 (0–12 months), Year 2 (13–24 months), and Years 1 and 2 (0–24 months).

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The data were analyzed using regression analysis, and the adjusted response surface model was:

$$Y = b_0 + b_1 N + b_2 N^2 + b_3 P + b_4 P^2 + b_5 K + b_6 K^2 + b_7 NP + b_8 NK + b_9 PK$$

where Y, Dependent variable; b_0–b_9, Regression coefficients; N, Nitrogen; P, Phosphorous and K, Potassium.

The significance of regression coefficients was tested, and new response functions were fitted only in cases of significant effects ($P \leq 0.05$). From the fitted equations, the maximum productivity and maximum economic efficiency (i.e. 90% of the maximum) were found, along with the nutrient doses required to reach them and estimate the productivity of the shoot fresh and dry matter. The critical levels of N, P, and K in the shoots were calculated by substituting the doses linked to the highest possible economic efficiency productivity in the corresponding equations, or were represented by experimental means, in cases where there were no significant effects.

N doses significantly influenced ($P \leq 0.05$) plant development only in Year 1, showing higher shoot productivities with increasing N supply. P and K doses did not affect the productivity ($P > 0.05$) (Table 1). In Year 1, N doses quadratically influenced the accumulated shoot fresh and dry matter productivities, and their respective adjusted equations are presented below:

$$\hat{y} = 7235 + 70.466x - 0.3972x^2 \ (R^2 = 0.88); \text{ and}$$
$$\hat{y} = 1457 + 14.617x - 0.0852x^2 \ (R^2 = 0.78).$$

N is the essential nutrient most required by plants, it plays a structural role (constituent of organic molecules), acts in multiple physiological processes, and its availability often limits plant growth and plant productivity (Hawkesford *et al.* 2023).

Other nutritional studies with moringa have shown the effect of fertilizers on plant growth. The production of pods and seeds of *M. oleifera* was enhanced by the combination of vermicompost (50 t/ha) and fertigation with NPK 19:19:19 (2 g/litre) in a study carried out in the province of Alexandria, Egypt (Atteya *et al.* 2021). In South Korea, the application of compost and NPK fertilizer sources has also encouraged higher *M. oleifera* shoot development (Sarwar *et al.* 2018). He *et al.* (2020) observed that the highest biomass in moringa plants in pots occurred with the supply of 1,425 kg N/ha, 290 kg P_2O_5/ha, and 290 kg K_2O/ha. Ndagi *et al.* (2023) observe significant differences in plant height and diameter on moringa seedling under organic and inorganic fertilizer treatments in Nasarawa State, Nigeria. Mastiholi *et al.* (2023) observed improvement in soil health and higher yields in moringa area under organic nutrition in Karnataka, India.

The maximum productivity estimated for accumulated fresh (10,360.3 kg/ha) and dry matter (2,084.0 kg/ha) were obtained with the supply of 88.7 and 85.8 kg/ha of N, respectively. These results represent a mean increase of 43% in relation to biomass produced without N addition. Relative to maximum economic efficiency productivity the results indicated that doses of 37.6 and 36.3 kg/ha of N led to the accumulation of 9,324.3 and 1,875.6 kg/ha of harvested fresh and dry matter, respectively, in Year 1. Therefore, adopting maximum economic efficiency productivity as a production target would represent an average reduction of 58% in N dose used in first year of cultivation.

The N, P, and K contents in the plant tissue (shoot) were not influenced ($P > 0.05$) by fertilization (Table 1). Therefore, the critical contents of N, P, and K in the shoot of plants after two years of cultivation are represented by the experimental means, which were 3.23 dag/kg for N, 0.41 dag/kg for P, and 2.18 dag/kg for K. The observed values are within the accepted optimal ranges for plant tissues (Silber and Bar-Tal 2019).

N doses quadratically and significantly influenced the N content in the shoots ($P \leq 0.05$) only in Year 1, and its adjusted equation was $\hat{y} = 50.4 + 0.5206x - 0.0031x^2$ (R^2 = 0.76). P and K contents in the shoot were not influenced by fertilization (Table 1). These outcomes justified that the generation of dry matter was only impacted by N dosages in Year 1 and that the nutritional value is the consequence of multiplying the dry matter acquired throughout the assessment period by the nutrient content.

The annual N extraction (critical accumulated content) in Year 1 was 65.24 kg/ha, obtained with the N dose for maximum economic efficiency (36.3 kg/ha of N). The annual N extraction in the other evaluation periods was 78.44 kg/ha (Year 2) and 71.30 kg/ha (Years 1 and 2), represented by experimental averages.

P and K accumulated contents were not influenced ($P > 0.05$) by fertilization (Table 1), and its annual extraction can be expressed by the mean after two years, which were 8.99 kg/ha for P and 48.81 kg/ha for K. The results fall within the generic ranges suggested by Silber and Bar-Tal (2019) for maximum yields in cultivated plants. The order of nutritional accumulation in the shoot of *M. oleifera* was N>K>P, which reflects the extraction of nutrients by plants.

M. oleifera has been reported in the scientific literature as a species with developing well in poor soils or with reduced fertilization (Mashamaite *et al.* 2021). In the present study, the plants demonstrated a great capacity for producing shoots even without the addition of nutrients to the soil. Under nutritional deficiency, plants can internally transport mobile nutrients to regions of active growth (Kirkby *et al.* 2023) and prioritize the allocation of biomass in reserve structures (Pereira *et al.* 2023), thus minimizing losses to their growth.

Thus, moringa plants in the present study may have prioritized the formation of the root system in the first year of cultivation, regardless of the NPK doses used, a situation that may have created better conditions for nutrient uptake in the second year of cultivation. Further research is required to clarify these questions regarding the distribution of nutrients and biomass among the many organs of fertilized and unfertilized moringa plants.

Briefly, it was concluded that the productivity of fresh and dry matter of the shoot of moringa plants was influenced only by N doses in the first year of cultivation, when the

Table 1 Shoot productivities in *Moringa oleifera* plants fertilized with NPK

Nutrient dose	Fresh matter productivity			Dry matter productivity			Nutrient content			Accumulated content		
	Year 1	Year 2	Years 1 and 2	Year 1	Year 2	Years 1 and 2	Year 1	Year 2	Years 1 and 2	Year 1	Year 2	Years 1 and 2
kg/ha	kg/ha			kg/ha			dag/kg			kg/ha		
N							*Nitrogen*					
0	6,986.5	11,783.9	9,385.2	1,383.4	2,805.5	2,094.5	3.35	3.00	3.19	47.63	83.27	67.89
40	10,080.6	11,164.8	10,622.7	2,102.0	2,489.2	2,295.6	3.52	2.98	3.26	73.77	74.03	74.32
80	9,095.0	12,573.2	10,834.1	1,714.7	2,826.8	2,270.7	3.43	2.96	3.22	66.79	82.33	76.62
160	8,424.5	11,193.0	9,808.7	1,640.1	2,512.4	2,076.3	3.46	3.00	3.26	55.86	74.14	66.37
Trend	L*Q*	NS	NS	L*Q*	NS	NS	NS	NS	NS	L*Q*	NS	NS
P_2O_5							*Phosphorus*					
0	8,661.7	11,738.4	10,200.0	1,818.2	2,618.0	2,218.1	0.45	0.37	0.42	8.34	9.51	9.10
45	8,352.4	9,808.9	9,080.7	1,662.6	2,250.2	1,956.4	0.47	0.37	0.41	7.85	8.51	8.17
90	9,083.2	13,116.3	11,099.7	1,751.3	3,095.0	2,423.2	0.43	0.38	0.40	7.74	12.29	9.87
180	8,489.2	12,051.4	10,270.3	1,608.1	2,670.8	2,139.4	0.46	0.37	0.40	7.54	9.85	8.81
Trend	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
K_2O							*Potassium*					
0	8,252.3	10,636.9	9,444.6	1,604.9	2,340.6	1,972.7	2.32	2.03	9.444.6	39.15	48.58	42.64
20	9,184.5	13,567.4	11,375.9	1,782.1	3,168.9	2,475.5	2.53	2.16	11.375.9	46.74	71.75	57.42
40	8,293.6	9,717.5	9,005.6	1,677.9	2,218.8	1,948.4	2.28	2.06	9.005.6	40.15	46.25	41.95
80	8,856.2	12,793.0	10,824.6	1,775.3	2,905.8	2,340.5	2.49	2.15	10.824.6	44.61	63.93	53.25
Trend	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

L, Linear response; Q, Quadratic response; NS, Not significant; * significant at 5%. Year 1, 0–12 months; Year 2, 3–24 months; Years 1 and 2, 0–24 months.

supply of 88.7 and 85.8 kg/ha of N led to the maximum estimated productivity for fresh (10,360.3 kg/ha) and dry matter (2,84.0 kg/ha). The critical contents in the shoot were 3.23 dag/kg (N), 0.41 dag/kg (P), and 2.18 dag/kg (K), while the annual extraction by plants was 78.44 kg/ha (N), 8.99 kg/ha (P), and 48.81 kg/ha (K).

SUMMARY

Moringa oleifera is an Asian tree species cultivated for its nutritional and medicinal properties. Present study was carried out during 2021 and 2022 at Federal Institute of Minas Gerais, São João Evangelista-MG, Doce River Valley, South-Eastern Brazil to determine NPK doses for Moringa and critical NPK levels in the shoot. The experimental design was a fractional factorial of the type $(1/2)4^3$, with 32 treatments set up in four blocks. The treatments represented combinations of doses of N (0, 40, 80, 160 kg/ha); P_2O_5 (0, 45, 90, 180 kg/ha); and K_2O (0, 20, 40, 80 kg/ha). Each experimental unit was composed of four seedlings arranged in a row. Plant shoot harvests were carried out every 60 days (January, March, May, July, September and November) for two consecutive years. The data were analyzed using regression analysis, and the adjusted response surface model was: $Y = b_0 + b_1 N + b_2 N^2 + b_3 P + b_4 P^2 + b_5 K + b_6 K^2 + b_7 NP + b_8 NK + b_9 PK$. The productivity of fresh and dry matter of the shoot of *M. oleifera* plants was influenced only by N doses in the first year of cultivation, when the supply of 88.7 and 85.8 kg/ha of N led to the maximum estimated productivity for fresh (10,360.3 kg/ha) and dry matter (2,84.0 kg/ha). The critical contents in the shoot were 3.23 dag/kg (N), 0.41 dag/kg (P), and 2.18 dag/kg (K), while the annual extraction by plants was 78.44 kg/ha (N), 8.99 kg/ha (P), and 48.81 kg/ha (K).

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