



RESEARCH

Optimizing NPS fertilizer application to enhance productivity of maize–bean intercropping on Ferralsols

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Abstract

Maize (*Zea mays* L.) and common bean (*Phaseolus vulgaris* L.) are major food crops that support smallholder farming systems, yet productivity remains low on Ferralsols due to nutrient limitations and low input use. Ferralsols are characterized by acidity, low cation exchange capacity, and limited availability of nitrogen, phosphorus, and sulphur, which constrains crop growth and yield. This study evaluated the effects of NPS (12–45–5, Zn 0.2%) fertilizer on growth, yield, and nutrient use efficiency of maize–bean intercropping on Ferralsols in the Eastern Agro-ecological Zone of Tanzania during the 2024/2025 short rainy season. The experiment was arranged in a randomized complete block design with three replications and fifteen treatments, combining sole maize, sole common bean, and maize–bean intercropping with seven NPS rates (0–180 kg ha⁻¹). NPS fertilizer was applied to maize in sole and intercropped systems, while sole common bean received no fertilizer, reflecting its capacity for biological nitrogen fixation. Increasing NPS rates significantly improved vegetative growth and yield of maize and enhanced vegetative performance of common bean through indirect soil nutrient effects in intercropping. Maize grain yield increased from 2.0–2.3 t ha⁻¹ in unfertilized treatments to 3.4–3.7 t ha⁻¹ at 120–150 kg ha⁻¹ NPS, with smaller gains at 180 kg ha⁻¹. Nutrient use and recovery efficiencies declined at higher rates, indicating diminishing returns. Application rates of 120–150 kg ha⁻¹ NPS balanced yield improvement and input efficiency, supporting targeted fertilizer recommendations for maize–bean intercropping on Ferralsols in tropical smallholder systems.

Keywords Food security · Legume–cereal interactions · Nutrient optimization · Smallholder farming systems · Sustainable crop production

1 Introduction

Maize (*Zea mays* L.) and common bean (*Phaseolus vulgaris* L.) are widely cultivated crops that support food systems, dietary quality, and rural livelihoods across many regions of the world. Maize is grown in more than 160 countries and

provides staple calories for large populations in Africa, Asia, and Latin America (Cairns et al. 2021; Kondwakwenda et al. 2022). Common bean is the most consumed legume globally and supplies protein, dietary fiber, and micronutrients, particularly in low- and middle-income countries (Epule et al. 2022; Jackson et al. 2022). Despite their importance, yields of both crops remain far below attainable levels in many production systems. Smallholder maize yields often remain below 2 t ha⁻¹, while bean yields frequently fall below 1 t ha⁻¹, largely due to soil nutrient limitations and uneven access to agricultural inputs (Galani et al. 2022; Li et al. 2024). These yield disparities indicate the need for nutrient management approaches that address the requirements of both cereals and legumes.

In Sub-Saharan Africa (SSA), maize and beans form the foundation of smallholder farming systems, with maize supporting household energy needs and beans contributing dietary diversity and income (Mudadirwa et al. 2023; Bezner Kerr And Wynberg 2024). Maize cultivation spans

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more than 30 million hectares in the region and supports over 300 million people, while bean production is concentrated in East Africa, where Kenya, Tanzania, Uganda, and Rwanda contribute substantially to regional supply (Bouët And Nimenya 2023). Uganda has developed into a major bean exporter, and regional trade has expanded in response to rising demand (Amongi et al. 2025; Kimani 2025). Productivity growth in cereal–legume systems has remained limited, partly due to declining soil nutrient balances and increasing climate variability, which affect nutrient availability and crop performance (Sime et al. 2024; Saleem et al. 2024).

Maize and beans are frequently grown in intercropping systems that influence resource capture and nutrient cycling. Differences in rooting depth, growth duration, and nutrient demand allow maize and beans to interact in ways that can alter nitrogen and phosphorus availability within the cropping system. Biological nitrogen fixation by beans may contribute to soil nitrogen pools, while maize can affect light interception and nutrient uptake dynamics, shaping competitive or facilitative interactions depending on soil fertility status (Birachi et al. 2021; Mlemba et al. 2025). Balanced nutrient supply is therefore central to sustaining positive interspecific interactions and reducing competition in maize–bean intercropping systems.

Within East Africa, Tanzania represents a major production and consumption zone for both crops. Maize occupies approximately 45% of arable land and contributes more than 70% of caloric intake, while beans support household nutrition and cross-border trade (Kihara et al. 2021; Utonga And Kamwela 2024). The Southern Highlands, including Mbeya, Songwe, Ruvuma, and Iringa, supply domestic and regional markets, and bean production supports trade with Kenya, Rwanda, and South Sudan (Maziku And Mashenene 2024; Kadigi et al. 2025). Yield levels in Tanzania remain below global averages due to long-term nutrient depletion and limited uptake of fertilizer technologies adapted to intercropping systems (Nchanji et al. 2021; Maereka et al. 2023; Magubika et al. 2025).

Soil-related limitations are pronounced on Ferralsols, which dominate large areas of tropical Africa and are characterized by acidity, low cation exchange capacity, and limited availability of nitrogen, phosphorus, and sulphur (Ratsiatosika et al. 2021, 2024). In Tanzania, fertilizer guidance for these soils is often generalized and rarely aligned with the nutrient dynamics of intercropping systems (Ayalew et al. 2022; Chivenge et al. 2022). Limited extension support for integrated soil fertility management further constrains farmers' ability to adjust nutrient inputs to local soil conditions (Ndegwa et al. 2023; Yamini et al. 2025). These conditions indicate a need for fertilizer recommendations that reflect both soil properties and cropping arrangements.

Compound fertilizers such as NPS formulations have attracted attention for supplying nitrogen, phosphorus, and sulphur in a single input (Chugh et al. 2021; Singh et al. 2024a). Previous studies have reported improved nutrient uptake and yield responses when NPS fertilizers are applied at rates matched to crop demand and soil characteristics (Srinivasarao et al. 2023; Romero Antonio et al. 2025). Evidence from maize–bean intercropping systems on Ferralsols in East Africa remains limited, as most studies emphasize monocropping or broad fertilizer recommendations.

This study evaluates the effects of different NPS fertilizer rates on growth, yield, and yield components of maize–bean intercropping on Ferralsols in Tanzania. It is hypothesized that balanced NPS application significantly enhances complementary interactions between maize and beans, resulting in higher system productivity than unfertilized or inadequately fertilized systems. The findings aim to support fertilizer recommendations that align with soil characteristics and intercropping practices in smallholder farming systems.

2 Materials and methods

2.1 Descriptions of the study area

The study was conducted during the 2024/2025 short rainy season at the Sokoine University of Agriculture (SUA) in Morogoro Region of Tanzania, specifically at the SUA Model Training Farm, situated at approximately 6.8430° S and 37.6543° E. The soil at this site is classified as Ferralsol, a common soil type in tropical regions, characterized by acidic and nutrient-poor properties. Morogoro experiences a tropical savanna climate, with distinct wet and dry seasons. The wet season occurs from November to April, with peak rainfall from March to May, while the dry season lasts from May to October. The altitude of Morogoro ranges from 300 to 600 m above sea level, which influences local climate conditions and agricultural potential. These climatic and soil conditions make the area an ideal location for practical learning and research focused on agricultural practices in tropical savanna environments.

2.2 Experimental design and experimentation

The treatments were arranged in a randomized complete block design (RCBD) with three replications to account for spatial variability across the field. The treatment structure consisted of combinations of cropping system and NPS fertilizer rate, resulting in a total of 15 treatments. Cropping systems included sole maize, sole common bean, and maize–common bean intercropping. Fertilizer treatments comprised seven NPS (12–45–5, Zn 0.2%) application

levels, expressed as 0, 30, 60, 90, 120, 150, and 180 kg ha⁻¹, where 120 kg ha⁻¹ represents the standard recommendation for maize.

Six NPS fertilizer rates (30, 60, 90, 120, 150, and 180 kg ha⁻¹) were applied to sole maize plots and to maize rows within maize–common bean intercrops. Common bean grown as a sole crop did not receive NPS fertilizer, considering its capacity for biological nitrogen fixation. Unfertilized control plots were included for sole maize, sole common bean, and maize–common bean intercropping to allow assessment of crop responses attributable to fertilizer application under both sole and intercropped conditions. This treatment arrangement resulted in six fertilized sole maize treatments, six fertilized intercropped maize treatments, and three unfertilized controls, giving a total of 15 treatments. With three replications, the experiment consisted of 45 plots.

Each experimental plot measured 3.6 m by 3.0 m. Replication blocks were spaced 1 m apart, while plots within a block were separated by 0.5 m. Each plot contained five rows of maize and, in intercropping treatments, four rows of common bean planted between maize rows. For sole cropping, common bean was planted in nine rows. Maize was sown at a spacing of 0.75 m between rows and 0.30 m within rows (one seed per hole), while sole common bean was planted at 0.40 m between rows and 0.10 m within rows. In intercropping, beans were inter-row planted between maize rows at 0.10 m spacing within rows. NPS fertilizer was applied to maize only, with 25% of the rate applied at sowing and the remaining 75% at 21 days after sowing. Other crop management practices included proper land preparation, planting, manual weed control, and supplemental irrigation.

2.3 Data collection

2.3.1 Soil sampling and laboratory analysis

Prior to planting, composite soil samples were collected from multiple locations across each experimental plot during the November 2024 to February 2025 short rainy season. Sampling followed a zig-zag pattern to account for variability in vegetation, soil colour, and topography. Samples were taken from the 0–30 cm soil depth and composited per plot. Laboratory analysis was carried out to determine the physical and chemical properties of the soil in accordance with standard procedures outlined by Okalebo et al. (2002).

Particle size distribution was determined using the hydrometer method, with dispersion facilitated using 5% sodium hexametaphosphate (Na₆[(PO₃)₆]), as described by Gee and Bauder (1986). Bulk density was measured from undisturbed core samples dried at 105 °C for 24 h. Soil pH and electrical conductivity were assessed in a 1:2.5 soil-to-water suspension using potentiometric techniques, following the protocol of Lindsay and Norvell (1978). Organic carbon was analyzed

using the Walkley–Black wet oxidation method (Nelson And Sommer 1996).

Available phosphorus was quantified using the Bray–Kurtz-1 method (Bray And Kurtz 1945), and total nitrogen was determined using the micro-Kjeldahl method (Bremner And Mulvaney 1982). Cation exchange capacity was measured with the neutral ammonium acetate (NH₄-Ac, pH 7.0) method followed by Kjeldahl distillation, as described by Chapman (1965). Exchangeable bases (K, Mg, Ca, Na) were extracted using 1 N NH₄-Ac (pH 7.0); Mg and Ca were quantified using atomic absorption spectroscopy (AAS), while K and Na were measured with an emission flame photometer. Micronutrients (Fe, Cu, Zn, Mn) were extracted using Diethylenetriamine pentaacetate (DTPA) and quantified by AAS. Extractable sulphur was analyzed using the turbidimetric method (Okalebo et al. 2002).

2.3.2 Agronomic use of nutrients

Data on total nutrient uptake was estimated by sampling aboveground biomass at physiological maturity and analyzing it for total nitrogen (N), phosphorus (P), and sulphur (S) contents to calculate nutrient uptake in kg/ha.

Agronomic use efficiency (AUE), also referred to as nutrient use efficiency (NUE), was calculated to determine the increase in grain yield per unit of nutrient applied, as shown in Eq. 1.

$$AUE = \frac{Y_f - Y_0}{F} \quad (1)$$

where Y_f is the grain yield (t/ha) from fertilized plots, and Y_0 is the grain yield from the control plot with no NPS application, and F is the amount of nutrient applied (kg/ha). Since NPS is a blended fertilizer, agronomic use efficiency was computed separately for each nutrient component, as shown in Eq. 1–4:

$$AUE_N = \frac{Y_f - Y_0}{N_{\text{applied}}} \quad (2)$$

$$AUE_P = \frac{Y_f - Y_0}{P_{\text{applied}}} \quad (3)$$

$$AUE_S = \frac{Y_f - Y_0}{S_{\text{applied}}} \quad (4)$$

Nutrient recovery efficiency (NRE) was used to estimate the proportion of the applied nutrient that was taken up by the maize crop, as shown in Eq. 5.

$$NRE = \frac{U_f - U_0}{F} \times 100 \quad (5)$$

where U_f represents the total nutrient uptake (kg/ha) from fertilized plots, U_0 is the nutrient uptake from the control plot, and F is the amount of nutrient applied (kg/ha). This calculation was similarly performed for N, P, and S separately:

2.3.3 Agronomic data

Growth measurements were taken at seven-day intervals throughout the cropping season. Parameters recorded included plant height, leaf area index, and aboveground biomass accumulation for both maize and common bean. These data allowed for monitoring vegetative performance under varying NPS fertilizer rates. At physiological maturity, yield data were collected from the net plot area. For maize, total aboveground biomass and grain yield were recorded. For common bean, yield components such as number of pods per plant, grains per pod, and 1000-grain weight were measured.

2.3.4 Climate data

Daily climate data, including maximum and minimum temperature and total rainfall, were recorded throughout the growing season using an on-site rain gauge and thermometer

installed near the experimental area. The monthly climate data from November 2024 to April 2025 showed average temperatures ranging between 23.64 °C and 26.15 °C, which fall within a generally favourable range for the growth of maize and common bean (Fig. 1). These temperatures support good germination, vegetative growth, and reproductive development for both crops.

Total precipitation varied considerably across the months, from as low as 42.03 mm in February to as high as 254.15 mm in March. Ferralsols, which are typically well-drained but have low nutrient availability and moderate to high acidity, may limit crop performance if soil fertility is not adequately managed. During the months with high precipitation such as December, January, March, and April, there should be sufficient soil moisture to support crop growth. However, excessive rainfall—particularly in March and April—may increase the risk of nutrient leaching in Ferralsols, potentially reducing nutrient availability to maize and common bean. Conversely, the relatively dry conditions in February could lead to water stress, especially if the crops are at sensitive growth stages. Because Ferralsols drain well, they do not retain moisture effectively, making the crops vulnerable to drought stress during dry periods unless supplemented by irrigation or moisture conservation techniques.

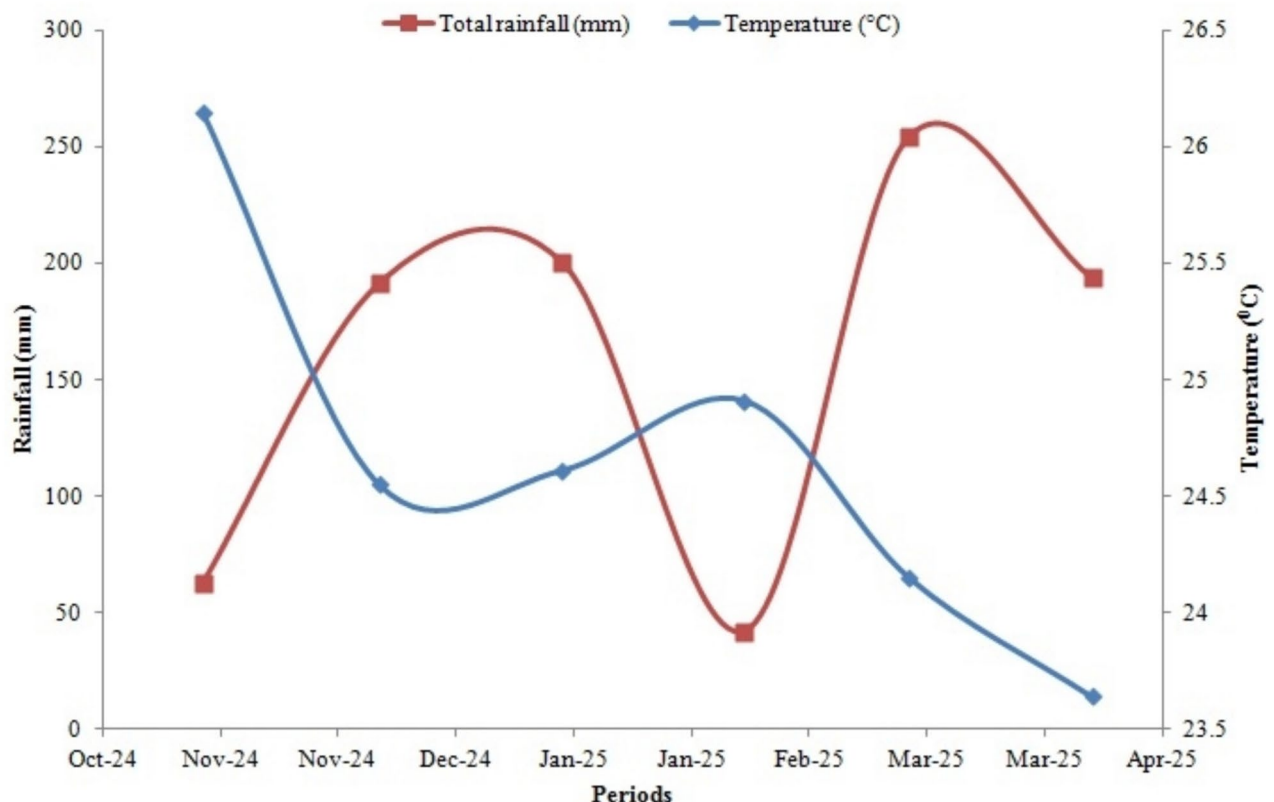


Fig. 1 Monthly average temperature (°C) and total precipitation (mm) from November 2024 to April 2025

The combination of moderate temperatures and fluctuating rainfall suggests that maize and common bean will benefit from adequate rainfall but may suffer yield reductions during dry spells. Therefore, optimizing soil fertility management and implementing water conservation strategies will be critical for achieving reasonable crop performance on Ferralsols under these climatic conditions.

2.4 Statistical data analysis

Statistical analysis was performed using GenStat 20th Edition to evaluate the influence of intercropping and NPS fertilizer application rates on the growth and yield performance of maize and common bean grown on a Ferralsol. Both one-way and two-way analysis of variance (ANOVA) were conducted to assess the main effects and interactions between cropping systems (sole vs. intercrop) and seven NPS fertilizer levels on vegetative growth parameters, biomass accumulation, and yield components. When significant treatment differences were detected ($p \leq 0.05$), mean separation was carried out using Tukey's Honest Significant Difference (HSD) test to identify statistically distinct treatment means. This approach ensured a robust assessment of the response patterns to fertilizer rates and cropping systems, allowing for accurate interpretation of the effects of integrated nutrient and cropping strategies on crop performance.

3 Results

3.1 Pre-planting soil characteristics

The pre-planting soil assessment reflects conditions typical of highly weathered Ferralsols in humid tropical regions (see Table 1). The strongly acidic reaction, combined with a low cation exchange capacity, points to a naturally constrained nutrient retention environment, which can limit the persistence of applied fertilizers. The clay-rich texture offers good water and nutrient-holding potential, yet poor drainage may influence root development and nutrient availability, particularly for sensitive crops. Macronutrient status reveals deficiencies in nitrogen and phosphorus, which are key drivers for early crop establishment and biomass production in maize–bean systems. Calcium is also limited, indicating a possible imbalance in the base cation profile, while magnesium and potassium are relatively favourable for crop growth. Micronutrient availability appears generally adequate, although zinc levels hover near deficiency thresholds, suggesting potential benefits from supplementation. Sulphur, iron, and manganese are present in sufficient quantities, reducing the likelihood of related constraints. In this context, optimizing NPS fertilizer application becomes especially relevant to address the nitrogen and phosphorus gaps while maintaining balanced nutrient supply for sustained intercropping performance on this soil type.

Table 1 Physico-chemical properties of pre-planting composite soil sample collected from the experimental field (0–30 cm depth) during the 2024/2025 short rainy season, with corresponding interpretations based on tropical soil fertility standards (Landon 1991)

Parameter	Value	Interpretation
pH (1:2.5) in H ₂ O	5.01	Strongly acidic
EC (μS/cm)	226	Low salinity
Clay (%)	54.1	
Silt (%)	9.6	
Sand (%)	36.2	
Texture Class	Clay	Poor drainage, high water and nutrient holding
Nitrogen (%)	0.14	Low
Organic carbon (%)	1.8	Moderate
Phosphorus (mg/kg)	2.24	Very low
Sulphur (mg/kg)	39.2	Sufficient
Calcium (cmol/kg)	0.63	Low
Magnesium (cmol/kg)	3.51	High
Sodium (cmol/kg)	0.19	Normal
Potassium (cmol/kg)	0.95	Adequate
CEC (cmol/kg)	7.28	Low – nutrient holding capacity limited
Copper (mg/kg)	2.66	Adequate
Zinc (mg/kg)	0.92	Marginal – near deficiency
Iron (mg/kg)	34.36	Sufficient
Manganese (mg/kg)	45.55	Sufficient

3.2 Effect of NPS fertilizer on maize growth and yield performance

The application of NPS fertilizer displayed a consistent trend of improving maize growth, with the most notable responses observed in plant height (Table 2). Growth gains followed a clear gradient with increasing rates, where plants under 180 kg ha^{-1} regularly reached over 120 cm by 63 DAE, compared to below 90 cm in unfertilized plots. Stem width differences emerged later in the season, with values approaching or exceeding 2.0 cm at 180 kg ha^{-1} , compared to around 1.5 cm in the control, indicating that structural robustness benefited from sustained nutrient input. Leaf number showed a less consistent pattern, but occasional differences were evident—such as at 49 DAE, when plants at 180 kg ha^{-1} produced about two more leaves than the control. Leaf area index trends reflected strong canopy expansion under higher fertilizer rates, peaking 21.1 cm^2 at day 35 in sole maize and above 16.0 cm^2 in intercrop at the same rate, whereas values for unfertilized plots remained below 12. Across both systems, the growth patterns were broadly similar, with intercropped maize occasionally exceeding sole maize—for instance, reaching 123.7 cm in height at 180 kg ha^{-1} versus 120.7 cm in sole cropping—highlighting that intercropping did not limit, and may sometimes slightly enhance, performance when nutrient supply was adequate.

Plant height patterns over the season revealed a steady increase with higher NPS fertilizer rates, particularly evident from day 35 onwards (Table 3). Early-stage growth

(days 21–28) showed little variation among treatments, with heights remaining close to 30 cm, indicating that initial emergence and establishment were less influenced by fertilizer rate. From day 35, however, differences became more apparent, with the highest rate (180 kg ha^{-1}) producing the tallest plants—reaching 71.7 cm in intercrop and 66.3 cm in sole maize—while the control remained around 59 cm and 57 cm respectively. This growth advantage persisted through later stages, culminating at day 63 with intercrop plants at 180 kg ha^{-1} attaining 123.7 cm, compared to 110 cm in the unfertilized treatment. Sole maize followed a similar pattern, peaking at 120.7 cm at the highest rate versus 108.3 cm for the control. Differences between intercropping and sole cropping were modest, though intercrop tended to produce slightly taller plants at the top fertilizer rate. The progression of values indicates that nutrient supply becomes increasingly influential after the early establishment phase, with the largest gains in height occurring between days 35 and 63 under higher NPS applications.

The data show the effects of varying NPS fertilizer rates combined with sole maize and maize-common bean intercropping systems on total biomass, 1000-seed weight, grain yield, and nutrient use efficiency (NUE) for phosphorus (P), sulphur (S), and nitrogen (N) in maize (Table 4). Significant ($p < 0.01$) differences among the treatments were observed for all measured parameters, demonstrating that both fertilizer rate and cropping system influenced maize growth and nutrient dynamics.

Table 2 Effects of fertilizer rates and cropping on number of leaves and leaf area index across different growth stages

Practice	NPS rates (kg/ha)	Number of leaves per plant						Leaf area index	
		Day 28	Day 35	Day 42	Day 49	Day 56	Day 63	Day 28	Day 35
Intercrop	0	12a	14a	17a	19a	21a	22a	5.3a	10.2bc
Intercrop	30	11a	13a	16a	17ab	20a	23a	3.5a	6.8bc
Intercrop	60	10a	13a	15a	17ab	19a	23a	5a	11bc
Intercrop	90	10a	13a	16a	18ab	20a	23a	3.9a	9.6bc
Intercrop	120	11a	13a	17a	19a	21a	23a	5.6a	8.4bc
Intercrop	150	11a	14a	16a	17ab	20a	23a	3.7a	8bc
Intercrop	180	11a	14a	17a	17ab	21a	23a	5.6a	11.3bc
Sole	0	11a	13a	16a	18ab	20a	23a	5.9a	12b
Sole	30	10a	13a	16a	17ab	19a	22a	4.1a	6.9bc
Sole	60	10a	13a	16a	18ab	20a	22a	3.5a	6.8bc
Sole	90	11a	14a	16a	17ab	20a	23a	5.1a	6.7c
Sole	120	10a	14a	15a	15b	19a	23a	6a	10.6bc
Sole	150	11a	13a	17a	18ab	20a	23a	6.3a	11.9bc
Sole	180	11a	13a	15a	16b	19a	22a	7.5a	21.1a
S.E.D		0.7	0.7	1	0.8	1	0.5	1.2	1.4
<i>p</i> value		0.604	0.177	0.256	0.007	0.51	0.19	0.325	<0.001

Key: S.E.D. = standard errors of the differences of the means. The means along the same column bearing different letter(s) differ significantly at 5% probability

Table 3 Effects of NPS fertilizer and cropping on maize plant height at various growth stages

Practice	NPS rates (kg/ha)	Plant height (cm)						
		Day 21	Day 28	Day 35	Day 42	Day 49	Day 56	Day 63
Intercrop	0	30a	49a	59.3gh	66.3de	80.3e	90.3ab	110gh
Intercrop	30	29.3a	49a	61.3efg	70.3bcd	83.3cde	92.7ab	111.3fgh
Intercrop	60	30.7a	53a	63de	72a-d	85.7b-e	95.3ab	114.7def
Intercrop	90	30.7a	51.7a	65 cd	72.3a-d	87.7a-d	94ab	115.3de
Intercrop	120	30.7a	54.3a	66.7bc	74a-d	89.7abc	96.7ab	118bcd
Intercrop	150	28.7a	53.7a	70.7a	74.3abc	91ab	95.7ab	119.3bc
Intercrop	180	33a	56a	71.7a	79.3a	93.7a	99.7a	123.7a
Sole	0	30.3a	46.7a	57.7h	62.3e	73f	86.3b	108.3 h
Sole	30	28.7a	50.7a	60.3fg	68.7cde	81.7de	92ab	110.7gh
Sole	60	29a	49.3a	62ef	71bcd	85b-e	92.3ab	113.7efg
Sole	90	30a	51.7a	63.3de	72a-d	86.3b-e	94.3ab	115def
Sole	120	31.3a	55a	66bc	73.3a-d	89abc	99a	116.7cde
Sole	150	28a	53a	67.7b	74.3abc	90.3ab	96.3ab	118.3bcd
Sole	180	30.3a	54a	66.3bc	76.7ab	90.7ab	98.3ab	120.7ab
S.E.D		2.5	2.8	0.6	2.2	1.8	3.4	1.1
p value		0.969	0.834	<0.001	0.847	0.132	0.858	0.674

Key: S.E.D. = standard errors of the differences of the means. The means along the same column bearing different letter(s) differ significantly at 5% probability

Table 4 Effects of fertilizer rates and practices on maize growth, yield components, and nutrient use and recovery efficiencies

Fertilizer rates and practice	Total biomass	1000-seed wt	Yield	Nutrient use efficiency (kg/ha)			Nutrient recovery efficiency (%)		
	(t/ha)	(g)	(t/ha)	P	S	N	P	S	N
T2	16.1ab	4.9efg	2.3efg	-	-	-	-	-	-
T3	11b	4.3 g	2 g	-	-	-	-	-	-
T4	14.8ab	4.8e	2.2e	113a	78.7a	124.3a	37.7a	26a	41.3a
T5	14.5ab	5.2de	2.4de	117.3a	78.3a	128a	39a	26.3a	42.7a
T6	12.6b	5.4de	2.5de	53.3b	36b	58b	8.7b	6b	9.7b
T7	12.8b	5.8cde	2.7cde	57b	41.3b	61.3b	9.3b	7b	10.3b
T8	13b	6.3b-e	2.9a-e	38.7b	28b	42b	4.3b	3b	4.7b
T9	13.1b	6.4bcd	3bcd	39.3b	29b	43b	4.3b	3b	4.7b
T10	14.3ab	6.8a-d	3.1a-d	33b	25b	35.3b	2.7b	2b	3b
T11	15.9ab	7.4ab	3.4ab	37.3b	29.3b	39.7b	3b	2.3b	3.3b
T12	13.8b	7abc	3.3abc	27.7b	21.7b	28.7b	2b	1.3b	2b
T13	20.6a	8a	3.7a	49b	36.7b	45.3b	3.3b	2.7b	3b
T14	17.3ab	7.6ab	3.5ab	41b	28b	30.7b	2.3b	1.7b	1.7b
T15	17.3ab	7.6ab	3.5ab	50.3b	31b	31b	2.7b	1.7b	1.7b
S.E.D	1.9	0.5	0.3	10.4	6.9	11.1	3.7	2.4	3.8
p value	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Key: T2=0 kg/ha NPS, sole maize; T3=0 kg/ha NPS, maize-common bean intercrop; T4=30 kg/ha NPS, sole maize; T5=30 kg/ha NPS, maize-common bean intercrop; T6=60 kg/ha NPS, sole maize; T7=60 kg/ha NPS, maize-common bean intercrop; T8=90 kg/ha NPS, sole maize; T9=90 kg/ha NPS, maize-common bean intercrop; T10=120 kg/ha NPS, sole maize; T11=120 kg/ha NPS, maize-common bean intercrop; T12=150 kg/ha NPS, sole maize; T13=150 kg/ha NPS, maize-common bean intercrop; T14=180 kg/ha NPS, sole maize; T15=180 kg/ha NPS, maize-common bean intercrop. S.E.D. = standard errors of the differences of the means. The means along the same column bearing different letter(s) differ significantly at 5% probability

Total biomass production varied considerably across the different NPS rates and cropping systems, with the highest biomass recorded at 150 kg/ha NPS under intercropping (20.6 t/ha), while significantly lower values were observed in the unfertilized intercropped maize (11 t/ha) and sole maize receiving 60 kg/ha NPS (12.6 t/ha). This variation reflects the differential response of maize to nutrient availability and cropping arrangement. The 1000-seed weight ranged from 4.3 g in unfertilized intercropped maize to 8 g at 150 kg/ha NPS under intercropping, indicating that fertilizer inputs and cropping system affect both biomass accumulation and seed development. Grain yield followed a similar trend, with the lowest yield in unfertilized intercropped maize (2 t/ha) and the highest yield at 150 kg/ha NPS with intercropping (3.7 t/ha), illustrating the importance of adequate fertilization in maximizing maize productivity.

Nutrient use efficiency, expressed in kg/ha, varied significantly among the treatments. Sole maize and intercropped maize both receiving 30 kg/ha NPS showed the highest nutrient use efficiencies for phosphorus (113–117.3 kg/ha), sulphur (78.3–78.7 kg/ha), and nitrogen (124.3–128 kg/ha), which corresponded with moderate biomass and yield values. In contrast, treatments with the highest biomass and yield, such as maize intercropped at 150 kg/ha NPS, exhibited lower nutrient use efficiencies (P: 49 kg/ha, S: 36.7 kg/ha, N: 45.3 kg/ha), suggesting that higher fertilizer rates and intercropping at this level may result in diminishing returns in nutrient efficiency, potentially due to luxury consumption or nutrient losses.

Nutrient recovery efficiency, which indicates the proportion of applied nutrients absorbed by the crop, also differed across treatments. The highest recovery rates were observed at 30 kg/ha NPS under both sole maize and intercropping systems (P: ~37–39.3%, S: ~26%, N: 41.3–42.7%), reflecting efficient nutrient uptake relative to fertilizer inputs.

Conversely, the highest biomass and yield treatment (150 kg/ha NPS under intercropping) showed much lower recovery efficiencies (P: 3.3%, S: 2.7%, N: 3%), implying that although yields were higher, nutrient absorption efficiency from fertilizers was reduced.

These results revealed a trade-off between achieving maximum yield and optimizing nutrient use efficiency. Applying 30 kg/ha NPS in both sole maize and maize-common bean intercropping supports moderate yields while maintaining high nutrient use and recovery efficiencies, which favours resource-efficient production. On the other hand, very high NPS rates, particularly at 150 kg/ha in intercropping, lead to increased biomass and yield but with reduced nutrient efficiency and recovery, indicating the need for careful nutrient management to prevent wastage and potential environmental impacts.

Both the amount of NPS fertilizer applied and the cropping system significantly influenced maize biomass, seed weight, grain yield, and nutrient dynamics. Moderately fertilized systems may provide a better balance between productivity and nutrient use efficiency, especially on Ferralsol soils that are prone to nutrient depletion and leaching.

3.3 Effect of NPS fertilizer on common bean growth and yield performance

Higher NPS fertilizer rates produced a clear and consistent improvement in common bean growth, with notable gains in leaf expansion, leaf elongation, plant height, and canopy spread (Table 5). Leaf area differences emerged early and became more pronounced over time, with plants at 90–180 kg ha⁻¹ regularly exceeding 110 cm² by day 49, compared to 101–104 cm² under the 0–30 kg ha⁻¹ rates. Leaf length followed a similar pattern, with higher rates supporting leaves of about 13 cm by day 49 versus around

Table 5 Leaf area and leaf length of common bean as influenced by varying NPS fertilizer rates

Fertilizer rates	Leaf area (cm ²) in days							Leaf length (cm) in days						
	7	14	21	28	35	42	49	7	14	21	28	35	42	49
Sole (0)	7.7a	19.1ab	51.5a	70.6a	84.8a	68.3ab	113.1a	5.3a	8a	10.7a	12.7a	13a	13a	13a
Intercrop (0)	6.8a	13.8b	25.1c	41.1d	58 cd	49.8d	103.7ab	4.7a	7a	8.7b	10b	12b	12.3ab	13a
30	5.8a	17.9ab	30.5bc	42.3d	52.2d	48.7d	101b	4a	7.3a	9ab	10.3b	12b	12.7ab	13a
60	9.4a	22.2ab	33.6bc	43.5 cd	60.9 cd	52.6 cd	110.2ab	4.3a	8.3a	8.7b	10b	12b	12b	12.7a
90	10.2a	24.7ab	35bc	54.1bc	69.6bc	56.9bcd	113.1a	4.7a	8a	9.7ab	10.7b	12b	13a	13a
120	8.7a	20.8ab	37.5abc	54.1bc	64.3 cd	53.3cd	113.1a	4a	7a	9ab	10.7b	12.7ab	12.7ab	13a
150	9.4a	23ab	44.7ab	63.8ab	82.7ab	64.3abc	113.1a	4.3a	7a	9.7ab	11b	12.7ab	12.7ab	13a
180	8.7a	27.1a	41.6ab	58.5b	78.5ab	70.6a	113.1a	6a	8a	9.3ab	11b	13a	13a	13a
S.E.D	1.9	3.7	4.4	3.2	3.8	3.7	3.4	0.9	0.7	0.5	0.4	0.2	0.3	0.2
p value	0.366	0.07	<0.001	<0.001	<0.001	<0.001	0.011	0.408	0.264	0.032	<0.001	<0.001	0.025	0.471

Key: S.E.D. = standard errors of the differences of the means. The means along the same column bearing different letter(s) differ significantly at 5% probability

10.7 cm in the unfertilized control. Leaf production was also strongly influenced, as plants at 180 kg ha⁻¹ reached 25 leaves per plant by day 49, while the control averaged fewer than 19. Height gains mirrored these trends, rising from about 25 cm at 0 kg ha⁻¹ to approximately 34 cm at 180 kg ha⁻¹ over the same period. The 90 kg ha⁻¹ and 150 kg ha⁻¹ treatments provided similar improvement across several parameters, indicating that mid-range rates can also substantially improve growth.

Fertilizer application influenced leaf production and plant height in common bean, with the effect becoming more pronounced as plants progressed through their growth stages (Table 6). In the early period (day 7–14), differences in leaf number were modest, but higher fertilizer rates, such as 180 kg ha⁻¹, already showed slightly greater values than lower rates. As the crop developed, these differences widened, with most treatments at 90 kg ha⁻¹ and above reaching around 24–25 leaves by day 49, while unfertilized plants and those at 30 kg ha⁻¹ often stayed near 23 leaves.

Plant height followed a similar trajectory, though it responded more gradually. In the first three weeks, growth was relatively uniform, ranging from 9–14 cm at day 7 and 16–21 cm by day 21, but from day 28 onwards, taller plants were generally associated with higher fertilizer levels. By day 35, plants in the top treatments approached or exceeded 31 cm, while those in the lowest rates were closer to 22–25 cm. Late-season measurements (day 49) showed reduced variation in height, with nearly all treatments converging around 33–34 cm, suggesting that lower-fertilized plants partially compensated in later growth. The pattern indicates that while nutrient supply accelerates early vegetative growth and maximizes leaf development, final plant height differences are less pronounced, hinting at a degree of growth recovery even in less-fertilized plants, though at the cost of reduced leaf production capacity.

Fertilizer application showed a marked influence on several key yield components of common bean, particularly pod production, seed set, and total biomass (Table 7). Pod

Table 6 Effect of NPS fertilizer rates on the number of leaves and plant height of common bean

Fertilizer rates	Number of leaves/plant in days							Plant height (cm) in days						
	7	14	21	28	35	42	49	7	14	21	28	35	42	49
0	2b	4.7a	8ab	11.7ab	14.7ab	24.3a	25a	11.7b	16ab	25.3a	29a	31.3a	34a	34a
0	2b	3.7a	7b	9b	13.3b	18.7d	23c	9.3 cd	11.7b	16.3c	20.3c	22.3c	25.3c	33.3a
30	2.3ab	5a	6.7b	10.3ab	13.3b	18.7d	23c	11bc	13.3ab	17.3bc	20c	22.7c	25.3c	33.3a
60	2.7ab	4a	7b	10.3ab	13.3b	21c	25a	10.7bcd	16ab	20.7b	25b	25bc	27bc	33.7a
90	2.7ab	4a	8ab	11ab	14ab	21c	24.3b	10.7bcd	14ab	20.3bc	26b	25.7bc	29.7abc	33.7a
120	2b	4a	7.7ab	12.7ab	14ab	22bc	25a	9d	12.3b	17.3bc	24b	28.7ab	31.7ab	34a
150	2.7ab	3.7a	8ab	13.3a	17a	23abc	25a	10.7bcd	13.3ab	21b	21c	29.3ab	32ab	34a
180	4a	5a	9a	13.7a	15.7ab	24ab	25a	13.7a	17a	20bc	20c	31.3a	33a	34a
S.E.D	0.5	0.4	0.5	1.1	1.0	0.6	0.2	0.5	1.3	1.2	0.6	1.6	1.6	0.3
p value	0.019	0.013	0.008	0.009	0.01	<0.001	<0.001	<0.001	0.008	<0.001	<0.001	<0.001	<0.001	0.099

Key: S.E.D. = standard errors of the differences of the means. The means along the same column bearing different letter(s) differ significantly at 5% probability

Table 7 Effects of NPS fertilizer on yield components of common bean

NPS rates (kg/ha)	Pods/plant	Seeds/pod	Dry wt (g/plant)	1000-grain wt (g)	Individual grain wt (g)	Grain yield (kg/ha)	Grain yield (t/ha)
0	13.3f	2.3e	4.3f	442.9d	0.4d	3075d	3.1d
30	15.3de	3de	4.4e	519c	0.5c	3604c	3.6c
60	16 cd	4cde	4.8d	561.9bc	0.6bc	3902bc	3.9bc
90	18.7b	7ab	6a	636a	0.6a	4417a	4.4a
120	17.3bc	5bcd	5.1c	571.4bc	0.6bc	3968bc	4.0bc
150	21a	7.7a	5.8b	638.1a	0.6a	4431a	4.4a
180	14ef	5.7abc	4.8d	598ab	0.6ab	4153ab	4.2ab
L.S.D	1.03	1.2	0.04	36.4	0.04	252.5	0.3
p Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Key: L.S.D. = Least Significance Difference. The means along the same column bearing different letter(s) differ significantly at 5% probability

numbers rose consistently with increasing rates, peaking at 21 pods per plant at 150 kg ha^{-1} compared to just 13.3 pods at the unfertilized control. This upper rate also produced the highest seeds per pod (7.7), more than three times the value in the control (2.3), with 120 kg ha^{-1} and 180 kg ha^{-1} also maintaining higher seed counts than the lower fertilizer rates.

Biomass accumulation followed a similar trend, with the greatest value of 1152.3 g per 20 plants recorded at 150 kg ha^{-1} , notably higher than the 942.5 g at 0 kg ha^{-1} . Although grain size indicators such as 1000-grain weight and 100-pod weight varied numerically across treatments—they did not differ significantly, suggesting that fertilizer influence was expressed more in the number of reproductive structures than in the size of individual grains or pods. Grain yield generally tracked the increases in pod and seed counts, with the highest yields of around 4.4 t ha^{-1} observed at both 90 kg ha^{-1} and 150 kg ha^{-1} , compared to 3.1 t ha^{-1} in the control. The overall pattern indicates that nutrient supply primarily enhances reproductive potential and biomass accumulation, while individual grain weight remains relatively stable across different fertilizer levels.

Fertilizer application markedly influenced all measured yield components of common bean (Table 7; Fig. 2). Dry

weight per plant ranged from 4.3 g at the control to 6.0 g at 90 kg ha^{-1} , with intermediate rates generally producing higher values than the unfertilized control. The 1000-grain weight increased from 442.9 g at the control to 638.1 g at 150 kg ha^{-1} , with several intermediate rates also showing substantial improvements. Individual grain weight rose from 0.4 g at the control to 0.6 g at most fertilized treatments. Grain yield followed a similar trend, increasing from 3075 kg ha^{-1} (3.1 t ha^{-1}) at control to the highest yields of 4417 kg ha^{-1} and 4431 kg ha^{-1} (4.4 t ha^{-1}) at 90 kg ha^{-1} and 150 kg ha^{-1} , respectively. Even the lowest fertilizer rate (30 kg ha^{-1}) showed yield improvement over the control, with progressive gains observed up to the optimal-performing rates.

4 Discussion

4.1 Maize and common bean performance

The results demonstrate that increasing NPS fertilizer rates led to marked improvements in vegetative growth parameters of common bean, including leaf area, leaf length, leaf number, plant height, and canopy width. These responses were consistent across sampling periods, with stronger responses

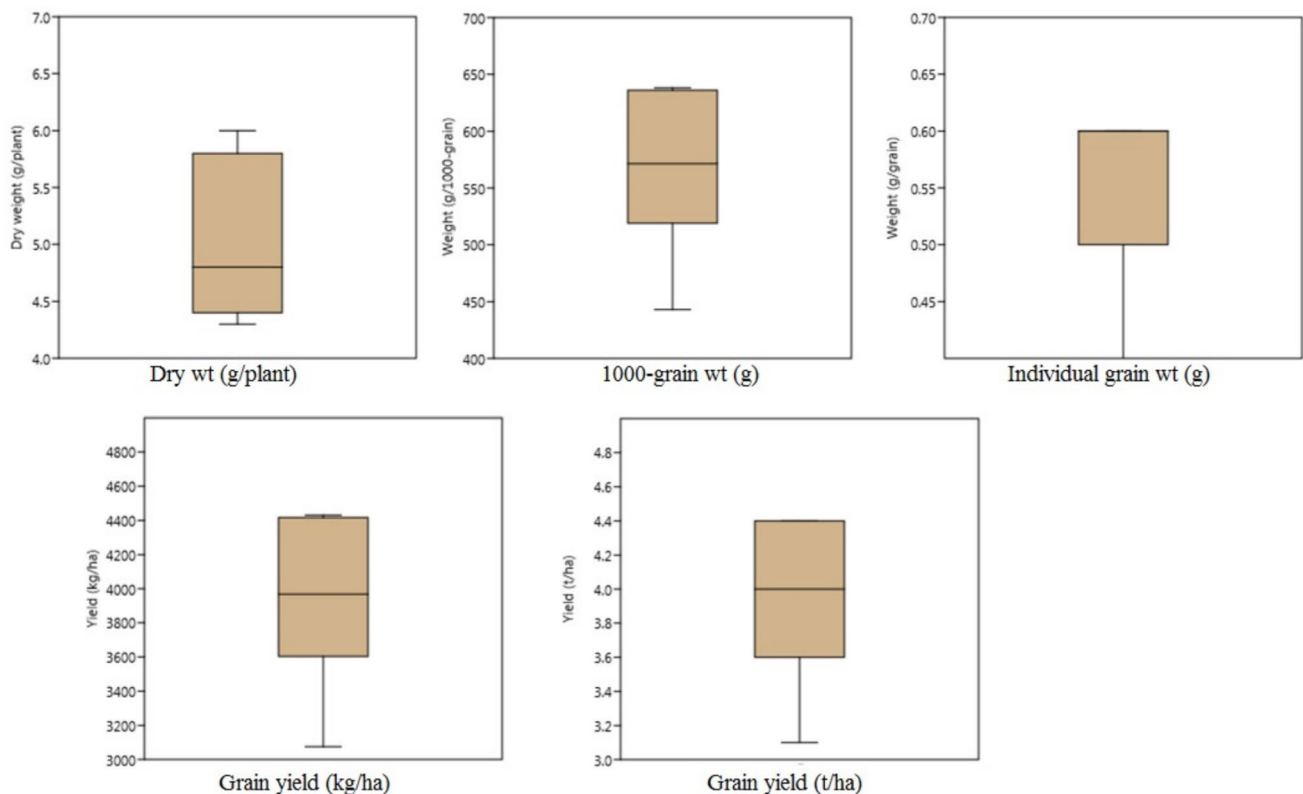


Fig. 2 Effect of varying NPS fertilizer rates on dry weight, grain size, and grain yield of common bean

observed at 150 and 180 kg ha⁻¹. Such trends reflect the sensitivity of bean growth to improved nutrient availability in Ferralsols, even when fertilizer was applied to maize within intercropped plots, supporting earlier findings that nutrient supply indirectly influences legume performance through modified soil nutrient dynamics (Hafez et al. 2021; Smith et al. 2022; Liu et al. 2024; Pudhuvai et al. 2024).

The progressive increase in leaf area with fertilizer rate indicates greater allocation to photosynthetically active tissue, which supports carbon assimilation and biomass accumulation. Larger and wider leaves observed at higher fertilizer levels align with reports that nitrogen availability promotes leaf expansion through enhanced cell division and chlorophyll formation (Longnecker 2021; Rahaman et al. 2021; Jaiswal And Dakora 2025; Wichaphian et al. 2025). Maintenance of higher leaf area later in the growth cycle suggests prolonged vegetative activity under improved nutrient supply, a pattern also reported in other legume studies (Stein et al. 2022; Arenas-Salazar et al. 2024). In intercropping systems, such leaf development may influence light interception dynamics between component crops, affecting spatial resource sharing rather than competition alone (Mugi-Ngenga et al. 2023; Dong et al. 2024).

Leaf number and plant height increased steadily with fertilizer rate, with the highest values recorded at 180 kg ha⁻¹. Enhanced leaf production under higher nutrient availability reflects increased meristematic activity and shoots development (Aoyagi et al. 2022; Mészáros et al. 2023; Yuan et al. 2023). Taller plants under higher fertilizer levels further indicate the role of nitrogen in promoting internode elongation and structural growth (Pinto et al. 2021; Salama et al. 2022; Gong et al. 2024; Zhou et al. 2024). In contrast, reduced height and leaf production under unfertilized or low-rate treatments point to nutrient constraints typical of Ferralsols, where nitrogen limitation restricts vegetative development (Guo et al. 2023; Al-Mamun et al. 2024).

Canopy width followed trends similar to other vegetative traits, expanding with fertilizer rate and time. Wider canopies observed at 150 and 180 kg ha⁻¹ reflect increased lateral growth associated with higher leaf number and leaf area (Gu et al. 2024; Wang et al. 2024a). Such canopy expansion enhances light capture and biomass production (Shen et al. 2023; Te et al. 2023) and may contribute to early weed suppression during crop establishment (Gazoulis et al. 2021; Merkle et al. 2024). In maize–bean intercropping systems, these canopy effects can modify the microenvironment, influencing resource availability for both crops and potentially supporting maize performance through reduced inter-row competition (Raza et al. 2021; Liu et al. 2022).

Across vegetative traits, responses increased sharply up to 150 kg ha⁻¹, while gains between 150 and 180 kg ha⁻¹ were smaller, indicating diminishing marginal returns at higher fertilizer rates (Sahoo et al. 2023). Similar plateaus have

been reported in common bean growth under elevated fertilizer inputs (Oyetunji et al. 2022; Yadav et al. 2023). Given the low nutrient retention capacity of Ferralsols, excessive fertilizer application may lead to losses through leaching, reinforcing the need for rate optimization rather than maximization (Ratsiatosika et al. 2021, 2024).

Enhanced vegetative growth observed in this study reflects physiological responses associated with improved nutrient availability and early crop vigour (Capo et al. 2023; Mwalugha et al. 2025). Although yield parameters were not evaluated in this phase, earlier studies have shown positive associations between vegetative development and subsequent reproductive performance in legumes and cereals (Welch 2024; Wang et al. 2024b). Lower performance at 0 and 30 kg ha⁻¹ further confirms inherent soil fertility constraints of the experimental site, emphasizing the role of balanced nutrient supply in maize–bean systems (Chivenge et al. 2021; Sapkota et al. 2021; Ogega et al. 2022; Wafula 2022). Under intercropping, appropriate NPS application supports coordinated growth between maize and beans, contributing to more efficient resource use within the system (Aulakh et al. 2022; Paramesh et al. 2023; Mutambu 2023).

4.2 Practical implications and challenges of the study

The findings illustrate how NPS fertilizer management influences crop growth on Ferralsols, soils that commonly limit nutrient availability in smallholder systems (Mashamaite et al. 2024; Singh et al. 2024b). Improved vegetative traits observed at moderate to high fertilizer rates indicate that targeted nutrient inputs can improve early crop establishment and canopy development in maize–bean intercropping systems (Gruda et al. 2024; Zhu et al. 2024; Ssemugenze et al. 2025; Han et al. 2025). These responses highlight opportunities for refining fertilizer recommendations to align with soil properties and cropping arrangements (An et al. 2023; Asante et al. 2025).

Economic considerations remain central to fertilizer adoption in smallholder farming. While higher fertilizer rates improved vegetative growth, diminishing responses beyond 150 kg ha⁻¹ suggest reduced efficiency at elevated input levels, which has direct implications for cost-effectiveness (Iatrou et al. 2025). Farmers operating under financial constraints are more likely to benefit from rates that balance input cost with measurable growth gains, particularly in environments characterized by variable rainfall and soil nutrient losses (Khanal et al. 2021; Penuelas et al. 2023; Shaffril et al. 2024; Pedersen et al. 2024). Linking fertilizer recommendations to nutrient use efficiency therefore remains important for practical decision-making.

Environmental considerations further shape fertilizer management on Ferralsols. Higher application rates increase

the risk of nutrient losses through leaching and runoff, with potential implications for soil condition and surrounding ecosystems (Hossain et al. 2022; Ramamoorthy et al. 2024; Xing and Wang 2024; Ali 2025). These risks reinforce the need for fertilizer strategies that prioritize efficiency rather than maximum input levels.

The study also contributes to locally generated evidence on fertilizer responses in intercropping systems under African soil conditions, addressing gaps in region-specific data (Lai et al. 2022; Mudare et al. 2022). Integrating such findings into extension and advisory frameworks can support context-appropriate nutrient management strategies. Continued refinement of fertilizer rates, combined with economic evaluation and longer-term yield assessment, will further strengthen recommendations for maize–bean intercropping on Ferralsols.

5 Conclusion and recommendations

This study shows that NPS fertilizer application improves vegetative growth and yield performance of maize–bean intercropping on Ferralsols, with stronger responses observed as application rates increased. Improved plant height, leaf area, and canopy development indicate that nutrient availability plays a central role in shaping crop growth under intercropped conditions. Although NPS fertilizer was applied to maize, common bean growth also responded positively, reflecting indirect effects mediated through altered soil nutrient dynamics, reduced competition, and interactions within the intercropping system. Application rates between 120 and 150 kg ha⁻¹ provided consistent growth responses while limiting diminishing returns observed at higher rates.

These findings support the use of moderate NPS fertilizer rates to improve maize–bean system performance on Ferralsols, particularly in smallholder settings where input efficiency is important. Future work should assess longer-term effects of repeated NPS application on soil nutrient status and system performance across seasons and locations. Such efforts will support refinement of fertilizer recommendations that align with intercropping practices and soil conditions in tropical environments.

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Declarations

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