

Soil-Plant Nutrient Dynamics and Fertilizer Use Efficiency in Maize & Desmodium Cropping System

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Abstract— Soil fertility decline and inefficient nutrient use remain major challenges limiting maize productivity in the arid and semi-arid lands (ASALs) of Kenya. This study evaluated the effects of integrating farmyard manure (FYM) with inorganic fertilizers on soil properties, nutrient uptake, yield performance, and efficiency indices in sole maize sole desmodium and maize-desmodium intercrop systems under field conditions in Keiyo North. The experiment consisted of six fertilizer substitution ratios (0-0, 25-75, 50-50, 75-25, 100-0, and 0-100% farmyard manure-inorganic N equivalence) arranged in a randomized complete block design with four replications. Soil chemical parameters (NH_4^+ , NO_3^- , pH, N, P, and C), plant nutrient uptake, and agronomic and recovery efficiencies were assessed. Results showed that combined farmyard manure – inorganic treatments, particularly 25-75 and 75-25, significantly improved soil nutrient status, enhanced N and P uptake, and increased maize and desmodium yields compared to sole applications. Farmyard manure -rich combinations improved moisture retention and microbial activity, sustaining nutrient release, while inorganic fertilizers ensured rapid early growth. Intercropping enhanced biological nitrogen fixation and nutrient recovery, leading to higher agronomic efficiency and resilience under moisture-limited conditions. The findings underscore that partial substitution of inorganic fertilizers with farmyard manure, coupled with maize-desmodium intercropping, offers a sustainable pathway to enhance soil fertility, nutrient use efficiency, and productivity in arid and semi-arid lands farming systems.

Keywords— Farmyard manure, nutrient use efficiency, soil fertility, ASALs.

I. INTRODUCTION

Declining soil fertility remains a major constraint to agricultural productivity in sub-Saharan Africa (SSA), largely due to continuous cropping, minimal nutrient replenishment, and poor fertilizer management practices (Ntinyari & Gweyi-Onyango, 2021). Excessive, improper, and unbalanced fertilizer use, particularly of nitrogen (N), has raised concerns over environmental degradation and soil health deterioration. Efficient nutrient management, particularly of nitrogen (N) and phosphorus (P), is therefore crucial to improving crop yield and sustaining soil productivity. The 4R principle, which entails applying the right source (fertilizer with higher efficiency), right rate, right time, and right placement, is recommended to enhance fertilizer use efficiency and reduce nutrient losses (Hochmuth et al., 2014). Proper placement and timing improve nutrient uptake by roots, minimizing leaching and gaseous losses. A promising strategy to further enhance efficiency is reducing nitrification through the use of nitrification inhibitors, which slow the microbial conversion of ammonium (NH_4^+) to nitrate (NO_3^-), thereby reducing N_2O emissions and nitrate leaching (Coskun et al., 2017).

While chemical nitrogen fertilizers have significantly increased crop yields globally, their long-term excessive use has led to adverse effects, including soil acidification, ammonia volatilization, non-point source pollution, and elevated nitrous oxide emissions (Hu et al., 2023). Similarly, phosphorus fertilizers, such as triple superphosphate (TSP), play an essential role in root development, energy transfer, and nucleic acid synthesis. However, phosphorus is relatively immobile in soils and prone to fixation, particularly in iron and aluminum-rich soils such as Ferralsols and Nitisols. This fixation renders phosphorus unavailable to plants, necessitating higher application rates that can, in turn, cause eutrophication of water bodies when excessive P is lost through runoff. Therefore, ensuring P is applied at the right time and in forms that minimize fixation is

essential. Studies show that balanced fertilization combining organic and inorganic sources enhances P availability and utilization, resulting in improved yields and reduced environmental impacts (Ntinyari & Gweyi-Onyango, 2021).

Organic materials such as farmyard manure (FYM) supply all the major nutrients (N, P, K, Ca, Mg, S) and essential micronutrients (Fe, Mn, Cu, Zn), acting as a comprehensive nutrient source. FYM application improves soil structure, enhances water holding capacity, stimulates microbial activity, and supports long-term soil fertility. Furthermore, FYM contributes to soil organic carbon (SOC) buildup, which enhances soil resilience, nutrient retention, and carbon sequestration potential. The combined application of FYM and mineral fertilizers has been shown to enhance soil fertility, reduce nitrogen losses, and increase crop productivity (Hu et al., 2023). For instance, (Zeyede et al., 2020) reported that combining manure with chemical fertilizers improved SOC by 2.45%, enhancing nutrient cycling and microbial activity. Although total organic carbon (TOC) changes slowly, labile organic carbon fractions, such as microbial biomass carbon (MBC), dissolved organic carbon (DOC), particulate organic carbon (POC), and easily oxidized organic carbon (EOC), respond rapidly to management interventions, serving as indicators of soil health (Z. Zhang et al., 2021).

Maize (*Zea mays*) is a staple crop in sub-Saharan Africa (SSA), where it accounts for up to 30% of the calorie intake of the population (Taylor & Tanumihardjo et al., 2010). Maize is also the most widely cultivated crop in the region, grown in 46 out of 53 countries in SSA (Abate et al., 2017). Despite the expansion in area under maize production, by 30.2% between 2007 and 2017, yield gains have been modest at only 8.5% (FAOSTAT, 2020). In Kenya, nitrogen and phosphorus deficiencies remain the most critical limitations to maize productivity (J. Kihara et al., 2016). High fertilizer costs and limited access (Nziguheba et al., 2016) have driven many smallholder farmers to rely on crop residues and manure to supply nutrients. However, these inputs often contain insufficient N and P to sustain high maize yields.

To address these challenges, intercropping maize with legumes has emerged as a promising strategy to improve soil fertility and productivity. Legume-based intercropping enhances nutrient cycling through biological nitrogen fixation, contributes organic matter, improves soil structure, and promotes more efficient resource use (Ndayisaba et al., 2021). Legumes can also increase phosphorus availability through the release of root exudates and organic acids that mobilize bound P, improving nutrient access for both crops in the intercrop.

Among potential intercrops, *Desmodium* (*Desmodium silverleaf*) stands out as a highly beneficial legume. It is a perennial, nitrogen-fixing forage crop known for its deep rooting system, high biomass production, and ability to improve soil fertility. *Desmodium* forms symbiotic associations with rhizobia to fix atmospheric nitrogen, enriching soil nitrogen pools. In addition, it exudes allelopathic compounds that suppress weeds like *Striga hermonthica* while enhancing phosphorus solubilization through organic acid secretion. These attributes make *Desmodium* an ideal intercrop with maize, improving overall nutrient efficiency, soil health, and system sustainability.

Efficient nutrient utilization is key to sustainable agricultural intensification. Nutrient use efficiency (NUE) reflects how effectively plants absorb and use applied nutrients for growth and yield. High NUE minimizes nutrient losses to the environment, while low NUE often results in nutrient accumulation in soils, leading to potential greenhouse gas emissions and environmental degradation. Optimizing NUE through balanced organic–inorganic fertilization is therefore critical for achieving sustainable yield gains while minimizing environmental footprints. This study aimed to: (i) Assess the impact of different organic–inorganic fertilizer combinations on soil chemical and physical properties in Keiyo North. (ii) Evaluate the nutrient use efficiency of maize and *Desmodium* under various fertilizer substitution ratios.

II. MATERIALS AND METHODS

2.1 Study Area:

This was an on-farm study conducted in Keiyo North sub-county of Elgeyo Marakwet County. The county is situated in Kenya's Rift Valley and covers an area of 3,029.6 km², representing 0.4 % of Kenya's total land area. It stretches from latitude 0° 20' to 1° 30' north and longitude 35° 0' to 35° 45' east. The county is mainly characterized by mixed crop, livestock, and agro-pastoral production systems, with key food crops including maize, beans, and green grams. The primary livestock enterprises are cattle (both dairy and beef), goats, sheep, and poultry (County Government of Elgeyo Marakwet, 2018). The area is situated at an altitude of 2804 Meters above sea level. Its climate varies from cool in the highlands, mild on the escarpment, too hot in the lowlands, with an annual mean temperature of 20.47 °C and rainfall of 127 mm spread over two rainy seasons. Figure 1 displays the map of the study site.

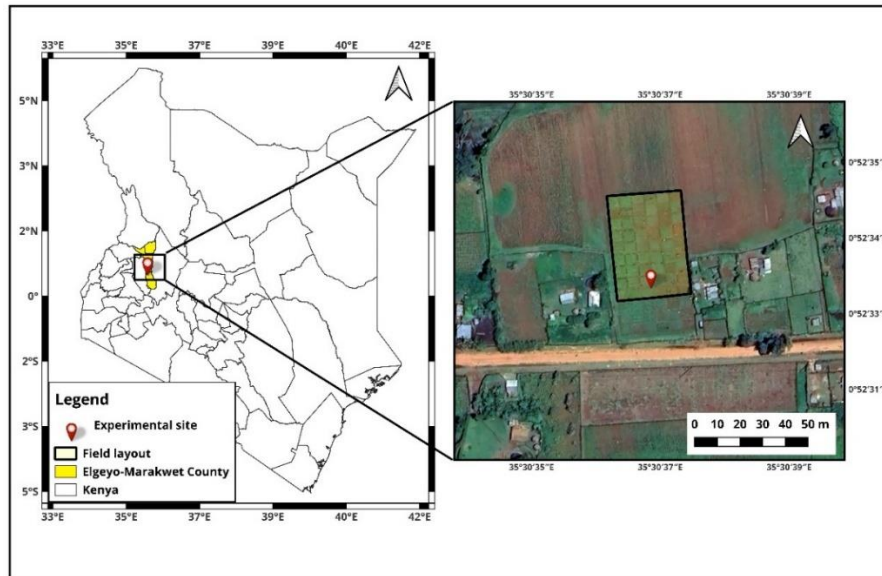


FIGURE 1: Map showing the location of the study site in Keiyo North in Elgeyo Marakwet County, Kenya

2.2 Experimental Setup:

The experiment was initiated in April 2024. The trial was laid out in a factorial experiment in Randomized Complete Block Design, with different Farmyard manure FYM and inorganic fertilizers substitution rates, under three cropping systems, namely, sole maize, sole *desmodium*, and maize-*desmodium* intercrop. The six fertilizer substitution rates were: (i) 0 FYM and 0 Inorganic – No fertilizer (Control); (ii) 25 75 - 25% of 30kg Pha-1 supplied by FYM, and 75% of 30kg Pha-1 supplied by Inorganic fertilizer; (iii) 50 50 - 50% of 30kg Pha-1 supplied by FYM and 50% of 30kg Pha-1 supplied by Inorganic fertilizer; (iv) 75 25 - 75% of 30kg Pha-1 supplied by FYM, and 25 % of 30kg Pha-1 supplied by Inorganic fertilizer; (v) 100 0 - 100% of 30kg Pha-1 supplied by FYM and 0% of 30kg Pha-1 supplied by Inorganic fertilizer; and (vi) 0 100 - 0% of 30kg Pha-1 supplied by FYM and 100% of 30kg Pha-1 supplied by Inorganic fertilizer. Fertilizer application rates in this experiment were calculated based on the phosphorus (P) requirement to avoid oversupplying other nutrients, particularly potassium (K) and nitrogen (N). When N was used as the basis for calculation, it resulted in excessive application of both P and K due to the fixed nutrient ratios in the manure fertilizer blends. This would have exceeded the intended target rates of 100 kg N ha⁻¹, 30 kg P ha⁻¹, and 60 kg K ha⁻¹. We applied Farmyard manure (FYM), Urea, Triple Superphosphate (TSP), and Muriate of potash (MOP). The plots measured 5m by 4.5 m, and the whole experimental plot will be 61 m by 32.5 m. The maize variety planted was H6213 with a spacing of 75 cm inter-row and 25 cm intra-row. The *desmodium* variety was *Desmodium* silverleaf with a spacing of 35 cm inter-row and drilled in line. Land preparation consisted of the incorporation of FYM and inorganic fertilizer before planting. Two maize seeds were planted per hole and later thinned to one to attain the recommended 44,444 plants spacing per hectare.

2.3 Laboratory analyses of soil samples:

Soil samples were collected from each plot once every month for the whole growing season using a 5 cm wide soil auger to a depth of 0-20 cm and 20-40 cm. The samples were stored in plastic zip-lock bags and then transported to the laboratory, and analyzed within 24 hrs for nitrate (NO₃⁻) and ammonium (NH₄⁺). The colorimetric method was used to determine NO₃⁻ and NH₄⁺, measured at 419 and 655 nm wavelength, respectively (Okalebo et al., 2002). Soil bulk density was not monitored monthly but determined once at the beginning of the experiment, since it remains relatively stable over a cropping season (Okalebo et al., 2002)). Soil texture was determined by the hydrometer method as described by (Bouyoucos, 1962). Soil moisture content was determined gravimetrically by oven-drying 20 g of fresh soil at 105 °C for 24 hours, with results expressed as the percentage change in weight from fresh to dry soil. For chemical analyses, air-dried soils were sieved through a 2 mm mesh. Soil organic carbon (%C) was determined by the Walkley-Black wet oxidation method using potassium dichromate, sulfuric acid digestion followed by titration with ferrous ammonium sulfate (Okalebo et al., 2002). Soil pH was measured in a 1:2.5 (soil: water) suspension using a calibrated glass probe pH meter (LBI-449, India). Available P was determined using the Olsen method, where soil was extracted with 0.5 M NaHCO₃ solution (pH 8.5) and the absorbance of the extract was measured

at 880 nm using a spectrophotometer. Total N (%) was measured calorimetrically after Kjeldahl digestion, with absorbance read at 650 nm (Bremner & Mulvaney, 1982).

2.4 Initial Soil Characterization:

Initial soil characterization of the experimental site is presented in Tables 1. Soil pH were moderately acidic and ranges from 5.2 to 5.3. Total N was low at (0.10%), while that of available P was low (< 10 mg kg⁻¹). Organic carbon levels were moderate with values ranging 2.1- 2.78%. The soils were classified as clay loam.

TABLE 1
INITIAL PHYSIOCHEMICAL PROPERTIES IN THE SOIL BEFORE EXPERIMENTAL SETUP; (KEIYO NORTH)

Soil Depth (cm)	Bulk Density (g cm ⁻³)	pH	Total Nitrogen (%)	Av. Phosphorus (mg kg ⁻¹)	Organic C (%)	Texture
0–20	1.22	5.3	0.11	9.06	2.64	Clay loam
20–40		5.2	0.09	6.11	2.2	

Values are means (n = 3)

2.5 Plant Data Sampling and Analysis:

Maize and *Desmodium* Biomass Measurement Maize biomass was determined by sampling 16 plants within each 3 m x 3 m plot. Leaves were sampled at silking (15 weeks after planting), while grains and stovers were collected at harvest, air-dried for twenty-one days, and the dry weight was recorded. *Desmodium* biomass was measured by sampling eight rows of 3 m x 3 m within each plot. The data collected from maize and desmodium biomass measurements were used to compare the effects of different fertilizer treatments on crop performance and to identify the best fertilizer management practices that increase crop yield. Biomass measurements were essential in calculating the nutrient use efficiency (NUE). The total Biomass produced (both maize and *desmodium*) under different fertilizer inputs can indicate how efficiently the crops use the available nutrients. Equation 1 to 5 adopts the formula described by (Congreves et al., 2021).

2.6 Grain Yield Determination:

The number of plants in each effective sampling area was counted manually and recorded. Total and subsample fresh weights of the heads were measured per net effective area. The subsample was taken to the University of Eldoret for air drying in the greenhouse. The dry weights of the subsample were then measured. Grains were separated from stovers, and their dry weights were recorded. The grain yields were expressed in tons per hectare (t ha⁻¹).

$$\text{Grain yield (t ha}^{-1}\text{)} = \left(\frac{\text{total sample fresh weight of cobs} \times \text{sub sample dry grain weight}}{\text{sub sample fresh weight}} \right) \times 10,000 \text{ m}^2 / 9 \text{ m}^2 \quad (1)$$

2.6.1 Agronomic Use Efficiency:

It was determined by calculating the difference in grain yield with N application and without it, and then dividing the results by the amount of N applied, indicated by the following formula.

$$\text{Agronomic N use efficiency} = \left(\frac{\text{grain yield with N application} - \text{grain without N application}}{\text{amount of N applied}} \right) \quad (2)$$

2.6.2 Grain N and P Uptake:

Dry grains were sampled in each treatment after harvesting period and ground into fine powder before analysis for P and N content as per the laboratory manual by Okalebo et al (2002). The amount of N and P uptake was calculated and expressed in kilograms per ha as indicated in the formulae.

$$\text{Nitrogen uptake (kg ha}^{-1}\text{)} = \left(\frac{\text{N content (}\frac{\text{mg}}{\text{kg}}\text{)}}{1000000} \right) \times \text{yield (kg ha}^{-1}\text{)} \quad (3)$$

$$\text{Phosphorus uptake (kg ha}^{-1}\text{)} = \left(\frac{\text{P content (}\frac{\text{mg}}{\text{kg}}\text{)}}{1000000} \right) \times \text{yield (kg ha}^{-1}\text{)} \quad (4)$$

2.6.3 Apparent Recovery:

It was determined by calculating the difference in total N uptake in above-ground biomass with and without N fertilization. The net amount of N absorbed was then divided by the amount of nutrient applied.

$$\text{Apparent recovery efficiency}(\%) = \left(\frac{\text{Total N uptake of fertilized plants} - \text{Total N uptake of unfertilized plant}}{\text{Fertilizer N applied}} \right) \quad (5)$$

2.7 Lab analysis: Nitrogen and Phosphorus Analyses for Plants

From each powdered sample of leaves, stovers, and grains, 0.3 g was mixed with 4.4 ml of digestion mixture (composed of hydrogen peroxide, sulfuric acid, selenium, and salicylic acid) and stored at 2°C in digestion tubes. The mixture was digested in a block digester at 360°C for 2 hours. After digestion, the mixture was cooled and transferred to 50 ml volumetric flasks. The solution was made up to volume with distilled water, and 5 ml aliquots were taken for analysis. Percentage N and P were determined separately using the colorimetric method described by (Okalebo et al. 2002). Using a spectrophotometer, N absorbance was measured at 650 nm, while P absorbance was determined at an 880 nm wavelength.

2.8 Statistical analysis:

Data were analyzed using R (version 4.4). For soil parameters (NO_3^- -N, NH_4^+ -N, Total N, C, P, and pH), a linear mixed-effects model was fitted with treatment and cropping system as fixed effects and replicate as a random effect. For plant nutrient data (%N and %P), a two-way ANOVA was used to assess differences among treatments and cropping systems. Post hoc comparisons were conducted using Tukey's HSD test at $p \leq 0.05$. Agronomic efficiency (AE) and recovery efficiency (RE) were analyzed through one-way ANOVA since only treatment effects were considered. Pearson correlation and principal component analyses (PCA) were performed to explore relationships among soil, plant, and efficiency variables. All data were visualized using ggplot2, showing mean \pm standard error bars and multivariate relationships.

III. RESULTS

3.1 Soil Nutrients Dynamics:

3.1.1 NO_3^- -N Concentration:

(Figure 2), shows that NO_3^- -N concentrations peaked between DAP 30 and DAP 180 in the 0–20 cm soil layer and steadily declined toward harvest (DAP 210).

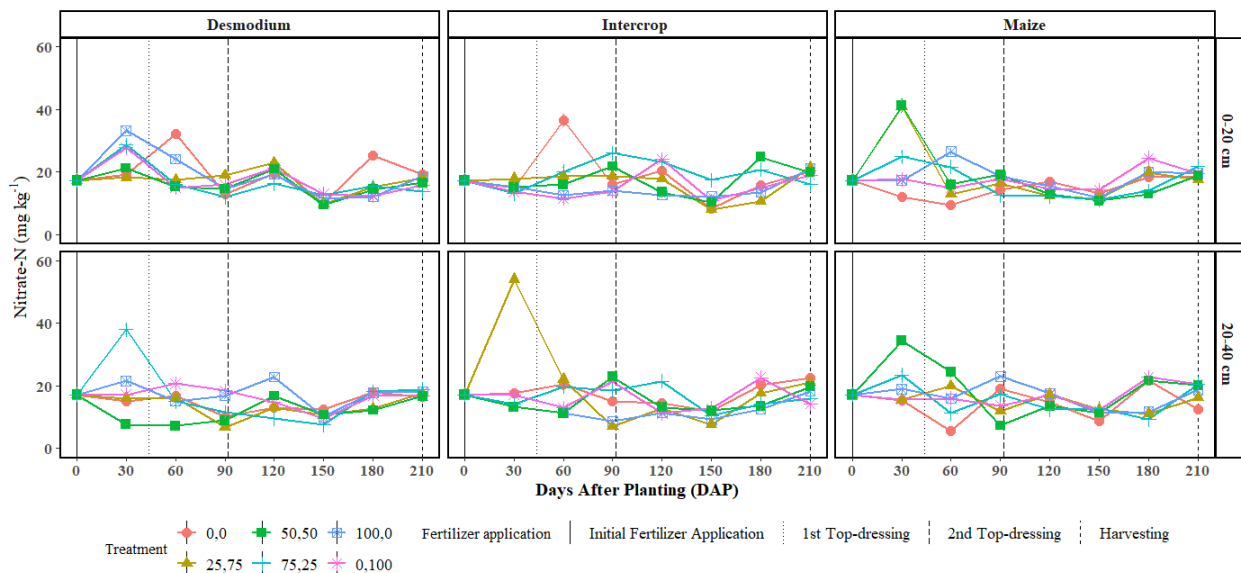


FIGURE 2: Soil Nitrate (mg kg^{-1} soil), for Desmodium, Intercrop & Maize Cropping System at 0- 20, 20-40 cm depth.

3.1.2 NH_4^+ -N Concentration:

Ammonium-N levels fluctuated over time as shown in figure 3, with peaks observed after DAP 30 and 90, especially in the 0–20 cm soil layer.

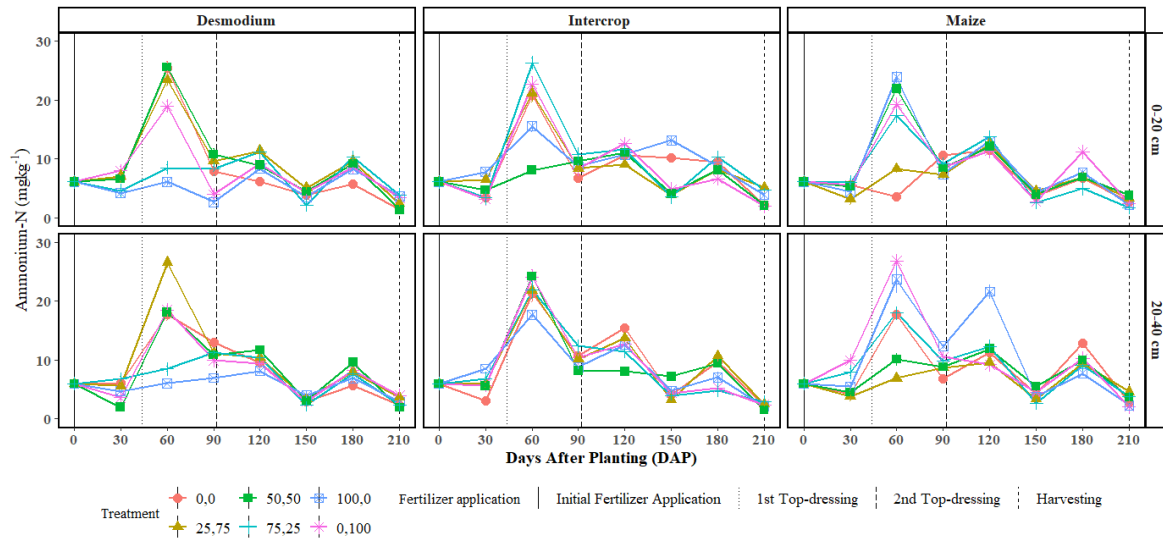


FIGURE 3: Soil Ammonium (mg kg⁻¹ soil), for Desmodium, Intercrop & Maize Cropping System at 0- 20, 20-40 cm depth.

These peaks aligned with periods immediately after the first topdressing, which involved urea fertilizer. The surface soils showed a range of 3.5–7.5 mg/kg, while in the 20 - 40 cm depth, values were generally lower (2.0–5.0 mg/kg). After DAP 120, a gradual decrease in NH₄⁺ concentrations were observed across all cropping system. Treatment 100,0 (FYM-only) and 75,25 (75% FYM + 25% inorganic) combinations consistently recorded the highest NH₄⁺ concentrations, with peaks reaching 22.5 mg/kg at DAP 60–90 in surface soils. Fertilizer treatments 0,100 (100% inorganic) and 0,0 (no fertilizer) had the lowest NH₄⁺ levels throughout the season, rarely exceeding 15 mg/kg even at peak times. The 25,75 and 50,50 fertilizer rates demonstrated intermediate values. *Desmodium* systems maintained higher NH₄⁺ concentrations for a longer period into the season, especially under 25,75, 75,25, and 100,0 fertilizer rates. The NH₄⁺ concentrations peaked at 25 mg/kg around DAP 60 and remained above 5 mg/kg even at DAP 150 in some plots. The maize-*desmodium* intercrop showed intermediate NH₄⁺ levels, peaking at 6.0–27 mg/kg at DAP 60 under the 50,50 and 75,25 treatments. Maize plots showed early peaks in NH₄⁺ (DAP 30–60), followed by a sharp decline by DAP 150, especially in the 0 100, 100 0, 25 75, and 75 25 fertilizer combinations. Peak NH₄⁺ levels for maize ranged from 15 to 25 mg/kg in the surface layer.

3.1.3 Soil pH:

Fertilizer treatment significantly affected soil pH (p < 0.001), with FYM-based treatments maintaining higher pH levels (6.3–6.5), while plots receiving 100% inorganic N (urea) showed lower pH (5.2).

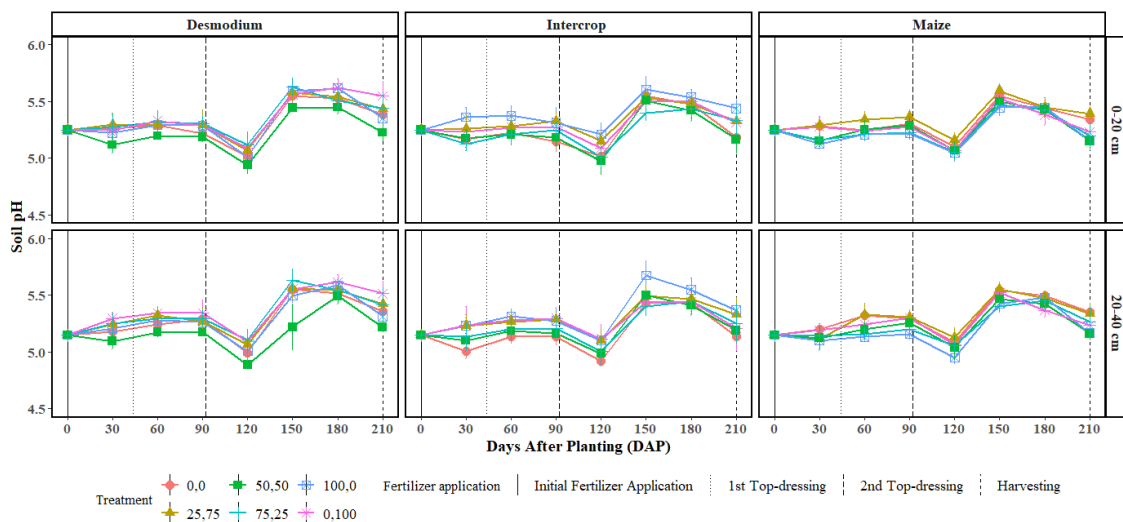


FIGURE 4: Soil pH, for Desmodium, Intercrop & Maize Cropping System at 0- 20, 20-40 cm depth

Soil pH values across all cropping systems ranged from 5.0 to 6.5, placing the soils in the slightly acidic to near-neutral range. The pH values were consistently higher in the surface layer (0–20 cm) than in the subsoil (20–40 cm) as shown in figure 3. Throughout the cropping season, a trend of pH increase was observed around DAP 90 and DAP 180, coinciding with topdressing fertilizer applications. Among the fertilizer treatments, plots amended with higher FYM to inorganic combinations (75,25 and 100,0) consistently maintained higher soil pH, especially in desmodium and intercrop systems.

3.1.4 Available Phosphorus:

Fertilizer treatments had a statistically significant effect on available phosphorus at 0–20 cm in $p < 0.05$, where FYM-rich plots (75,25 and 50,50) exhibited higher P levels (mean > 10 mg/kg). At deeper depths (20–40cm) the differences were not significant ($p > 0.05$), indicating that P dynamics are localized at the surface as shown in figure 5a. Across the three cropping systems, available phosphorus (P) concentrations displayed clear temporal trends. Values increased significantly from DAP 0 to DAP 90–150, then slightly decreased by harvest (DAP 210). The most notable increases occurred in the 0–20 cm depth. Available P ranged from as low as 4 mg/kg in 0,0 (control) to over 20 mg/kg in 50,50 and 75,25 fertilizer regimes, at peak times (DAP 150). As shown in Figure (5a)

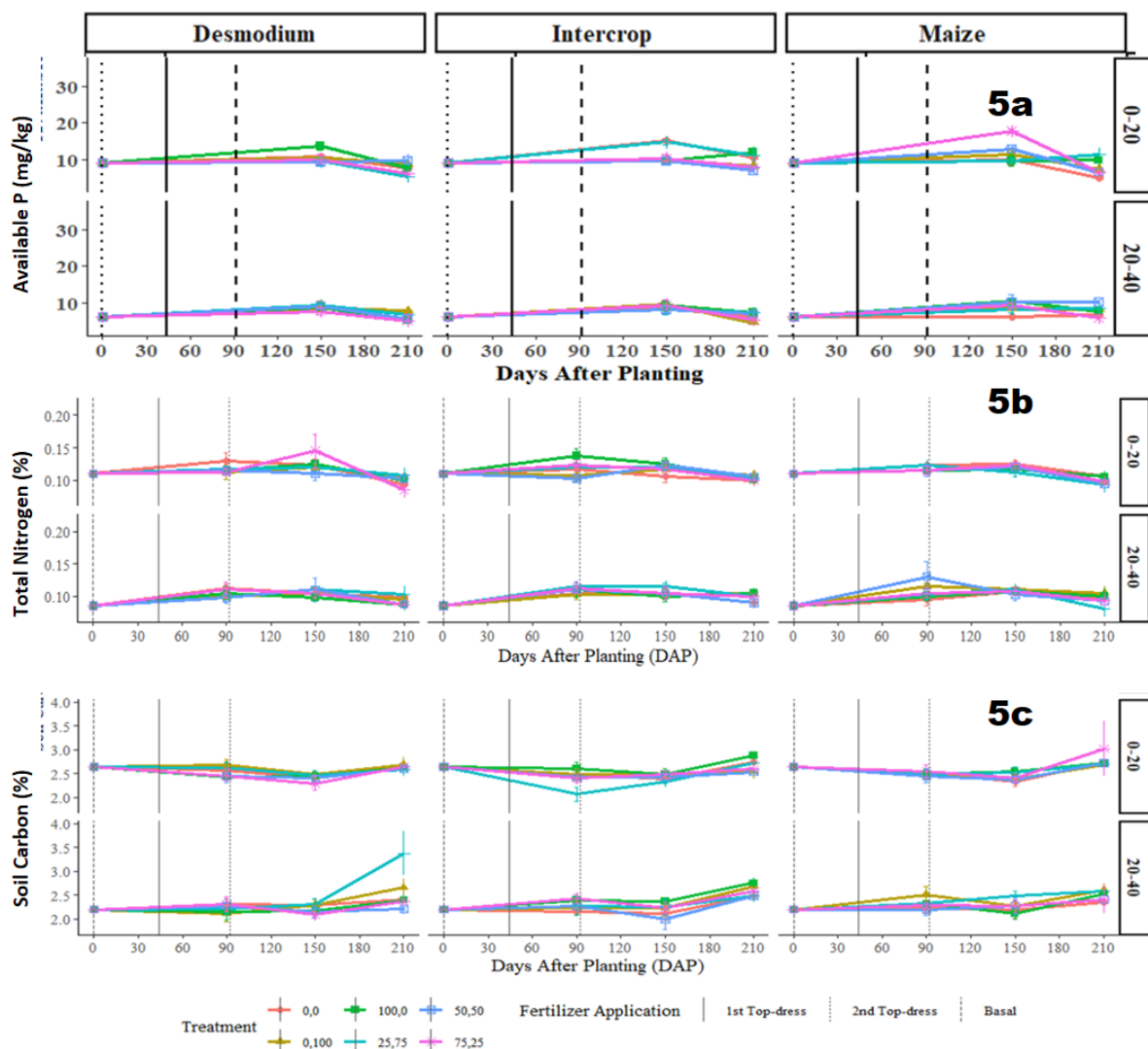


FIGURE 5a: Soil Available Phosphorus (mg/kg), (5b) Soil Nitrogen (%), (5c) Soil Carbon (%), for Desmodium, Intercrop & Maize Cropping System at 0- 20, 20-40 cm depth.

Desmodium plots consistently maintained higher available P, especially at the 0–20 cm depth. Peak values in 75,25 and 50,50 reached up to 24 mg/kg at DAP 150, declining slightly to 18 mg/kg at harvest. The intercrop exhibited intermediate but stable P concentrations, typically ranging from 14 to 20 mg/kg under FYM-inclusive treatments. Sole maize systems showed greater variability and faster P decline, particularly by DAP 180 to 210, even under 50,50 and 75,25. Although values reached 20

mg/kg at DAP 150, they dropped to 12–14 mg/kg at harvest. Deeper layers (20–40 cm) under maize often remained below 10 mg/kg.

3.1.5 Soil Total Nitrogen:

There were no statistically significant differences in total soil nitrogen across treatments and depth (ANOVA $p > 0.05$). Total nitrogen (%) exhibited a clear temporal pattern across all cropping systems and treatments as shown in figure 6. The initial values at DAP 0 were relatively consistent and low, Nitrogen concentrations rose by DAP 90 and a peak in total N was consistently observed around DAP 150, Subsequently, N levels declined toward DAP 210 (harvest). The 0–20 cm depth consistently showed higher nitrogen percentages than the 20–40 cm layer across all treatments and cropping systems. The 50,50 (50% FYM + 50% inorganic) and 75,25 fertilizer combinations maintained the highest total N concentrations throughout the season. In contrast, 0,0 (no fertilizer) and 0,100 (sole inorganic) plots consistently had lower total nitrogen values across the season. Meanwhile, 0,100 exhibited sharp declines post-DAP 90, especially in maize systems. *Desmodium* plots consistently recorded higher nitrogen concentrations, especially in the surface layer (0–20 cm) as shown in (5b) Even the 0,0 *desmodium* plots maintained relatively stable N levels compared to maize.

3.1.6 Soil Total Organic Carbon:

In figure (5c), Soil organic carbon was minimally impacted by fertilizer treatments at both depths ($p = 0.069$). The highest carbon levels were seen under 75,25 and 100,0 fertilizer combinations (means = 2.93% and 2.91%, respectively). Across all cropping systems and treatments, SOC was consistently higher at 0–20 cm than at 20–40 cm. Fertilizer treatments had a pronounced influence on soil carbon levels. Plots receiving high FYM inputs, 75,25 (75% FYM) and 100,0 (100% FYM), recorded the highest SOC concentrations, reaching up to 2.1% in topsoil by DAP 150, particularly under *Desmodium* and intercrop systems. Plots under 0,0 (no fertilizer) and 0,100 (100% inorganic fertilizer) had the lowest SOC values across all depths, generally remaining below 1.0%. The 25,75 and 50,50 fertilizer rates, which combined FYM with mineral fertilizers, showed intermediate SOC levels (1.2–1.7%). The *Desmodium* cropping system consistently exhibited the highest SOC values, especially at the 0–20 cm depth and during the mid-season (DAP 90–150). Peak SOC levels in *desmodium* plots with 75,25 and 100,0 reached approximately 2.1%, which was significantly higher than maize or intercrop. The intercrop system showed moderate SOC values, generally ranging from 1.2–1.8% in surface soils. The FYM-rich combinations under intercropping (50,50 and 75,25) maintained stable SOC levels throughout the season. Sole maize plots had the lowest SOC content, especially under 0,0 and 0,100 fertilizer rates. Maximum values were rarely exceeded at DAP 150, and subsoil values dropped to approximately 0.4–0.6%. In FYM-treated plots (50,50 and 75,25), SOC levels improved, reaching around 1.7%, but remained lower than *desmodium*.

3.2 Crop Performance and Plant Nutrition:

3.2.1 Maize grain Yield:

Grain yield maize monocrop varied significantly across treatments ($p < 0.05$), ranging from approximately 4.5 t/ha in the 0,0 treatment to a peak of about 6.8 t/ha under the 0,100 treatment as shown in figure 6.

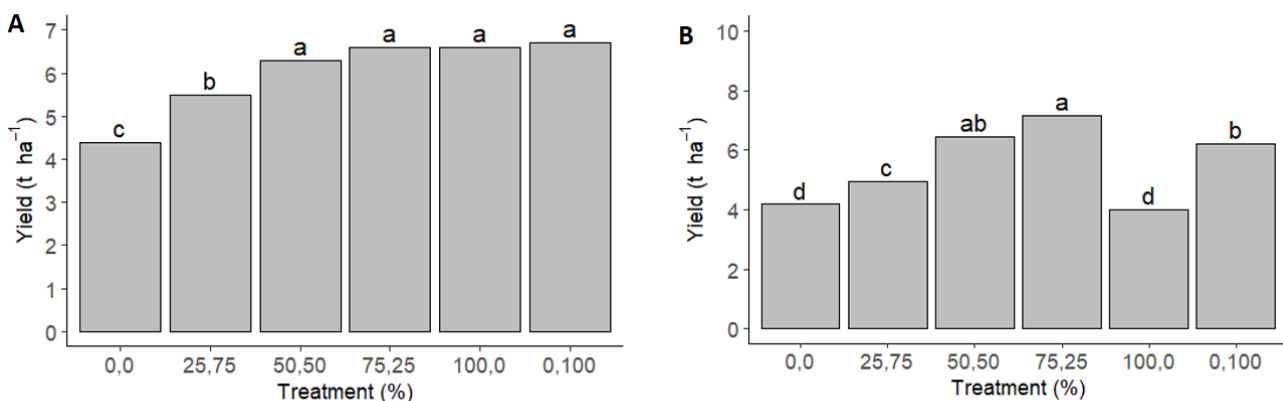


FIGURE 6: A & B are Maize Monocrop and Maize Intercrop Yield Respectively.

Grain yields were generally lower (4.5–6.5 t/ha), possibly due to reduced soil fertility. The highest yields were observed under 50,50, 75,25, and 100,0 fertilizer rates, all of which were statistically similar (6.0–6.5 t/ha). The lowest yield (4.5 t/ha) in the 0,0 treatment. In comparison, the moderate yield under 0,100 (6.0 t/ha). In the intercrop system, yields ranged from approximately 4.5 t/ha (0,0 and 100,0) to around 8.0 t/ha under 50,50 and 75,25, which were statistically the highest

3.2.2 Nitrogen Uptake (kg N ha^{-1}):

In maize monocrop, nitrogen uptake ranged from about 60 kg N/ha (0,0) to approximately 90 kg N/ha (50,50, 75,25, 100,0, and 0,100), all of which were statistically similar (Figure 7 a). N uptake was consistently higher across all rates, ranging from approximately 60 kg N/ha (0,0) to around 95 kg N/ha (50,50, 75,25, 0,100). Statistically, all treatments except the control (0,0) and 25,75 performed similarly (Figure 7 b).

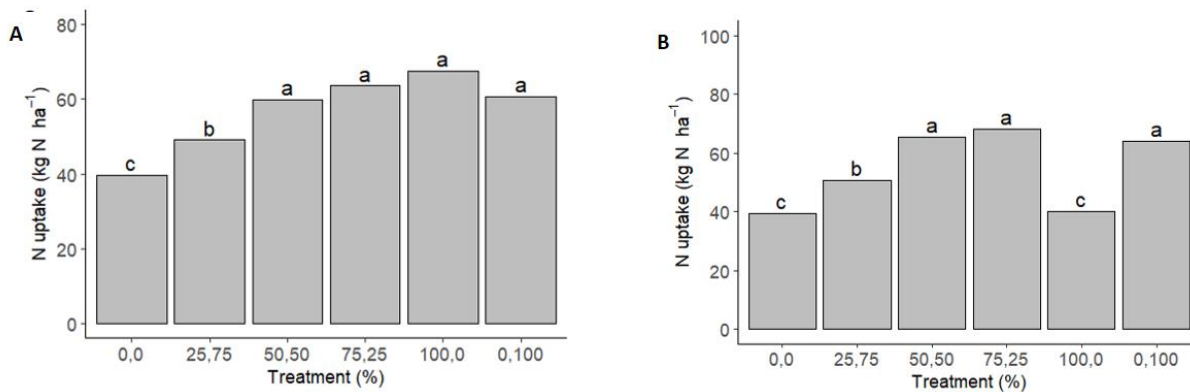


FIGURE 7: A & B are Maize Monocrop and Maize Intercrop N Uptake (kg N ha^{-1}) Respectively.

3.2.3 Phosphorus Uptake (kg P ha^{-1}):

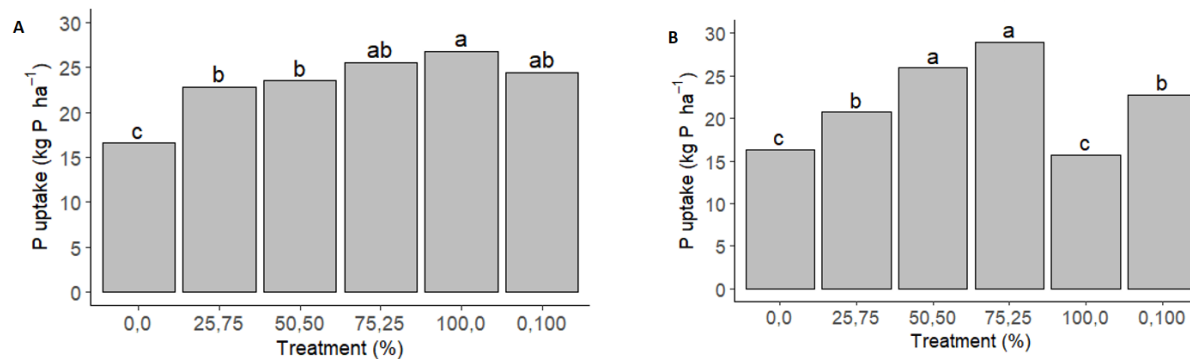


FIGURE 8: A & B are Maize Monocrop and Maize Intercrop P Uptake (kg P ha^{-1}) Respectively.

P uptake ranged from about 16 kg/ha (0,0) to 27 kg/ha (75,25) (Figure 8 a), with all treatments, including FYM (50,50, 75,25, 100,0), performing well. Intercrop, P uptake was highest under the 75,25 and 50,50 fertilizer rates (28–30 kg/ha), significantly greater than under the 0,0 and 100,0 treatments (17 kg/ha) (Figure 8 b).

3.3 Desmodium Biomass Yield:

Desmodium yield varied significantly ($p < 0.0001$) across treatments and cropping systems. Under sole *desmodium* cropping, yield ranged from 1.86 t/ha (0,0) to a maximum of 6.29 t/ha (75,25). The highest yield under intercrop was observed with 75,25 (FYM) at 2.42 t/ha, followed by 0,100 (2 t/ha) and 100,0 (1.84 t/ha) as shown in figure 9 D. Notably, intercropped *Desmodium* in the control (0,0) recorded the lowest yield (0.77 t/ha), indicating the necessity of nutrient input.

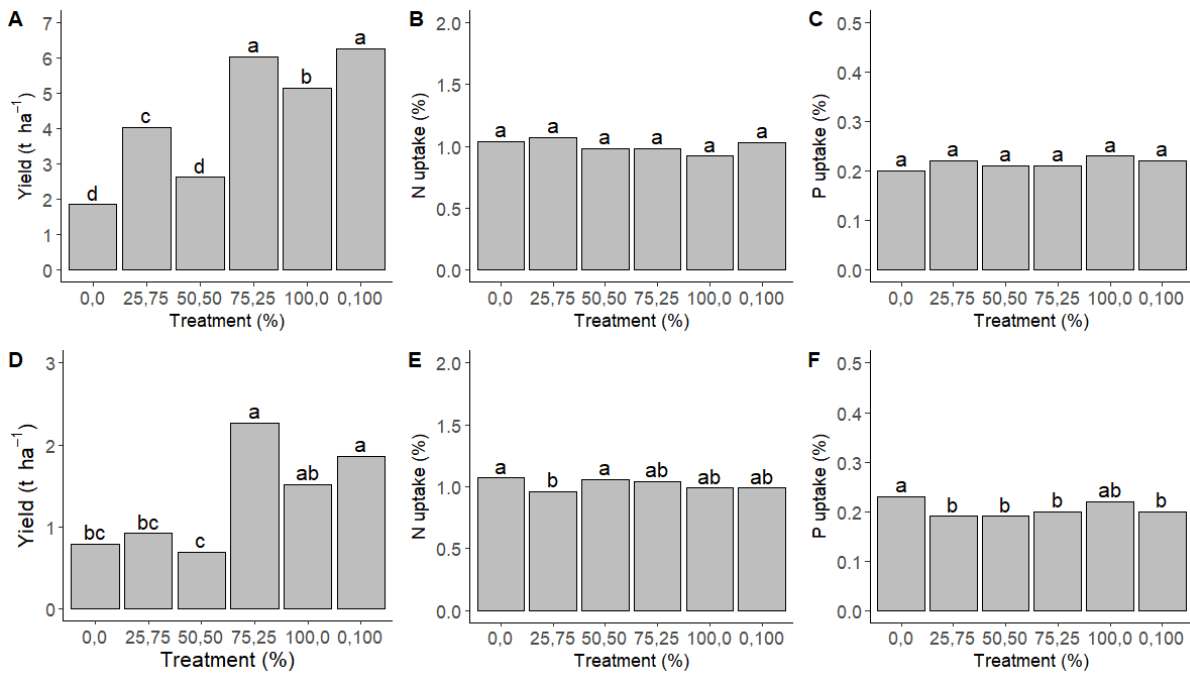


FIGURE 9: A-Yield (t/ ha⁻¹), B- N Uptake (kg N ha⁻¹), C- P Uptake (kg P ha⁻¹) for Desmodium Monocrop and D- Yield (t/ ha⁻¹), E- N Uptake (kg N ha⁻¹), F- P Uptake (kg P ha⁻¹) for Desmodium Intercrop.

3.3.1 Nitrogen Uptake (% N):

(Figure 9 b), shows a statistically significant effect observed ($p < 0.0001$), with generally higher N content in intercrops (mean = 1.01%) compared to sole crops (0.89%). The highest N uptake was observed under intercrop with 50,50 and 75,25, both at 1.06–1.04%, whereas the lowest was under sole cropping at 0,100 (0.97%).

3.3.2 Phosphorus Uptake (% P):

(Figure 9 c & f), shows both sole and intercropped *Desmodium* showed high P uptake across the fertilizer regimes, ranging between 0.20–0.23%. Notably, 0,0 still exhibited the highest %P in monocrop (0.99%) and intercrop (0.23%).

3.4 Nutrient Use Efficiency:

3.4.1 Agronomic efficiency AE:

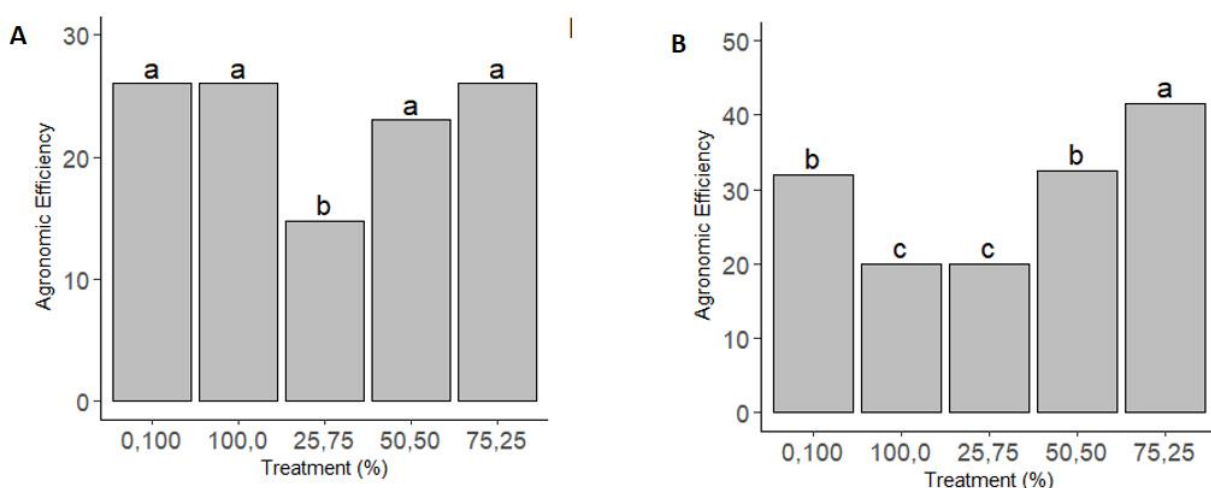


FIGURE 10: A & B is Maize Monocrop and Maize Intercrop Agronomic Efficiency Respectively.

For maize monocrop, (Figure 10 a), AE was highest in the 25,75 and 75,25 combinations (around 35 kg/kg), followed by the 50,50 ratios (about 30 kg/kg). The 100,0 ratio had the lowest AE (around 15). For maize in intercrop (Figure 10 b), the 75,25

fertilizer combinations showed the highest AE (40 kg/kg), while the 25,75 and 50,50 ratios ranged from 25 to 30. FYM-only and 0,100 had poor agronomic efficiency.

3.4.2 Recovery Efficiency (RE):

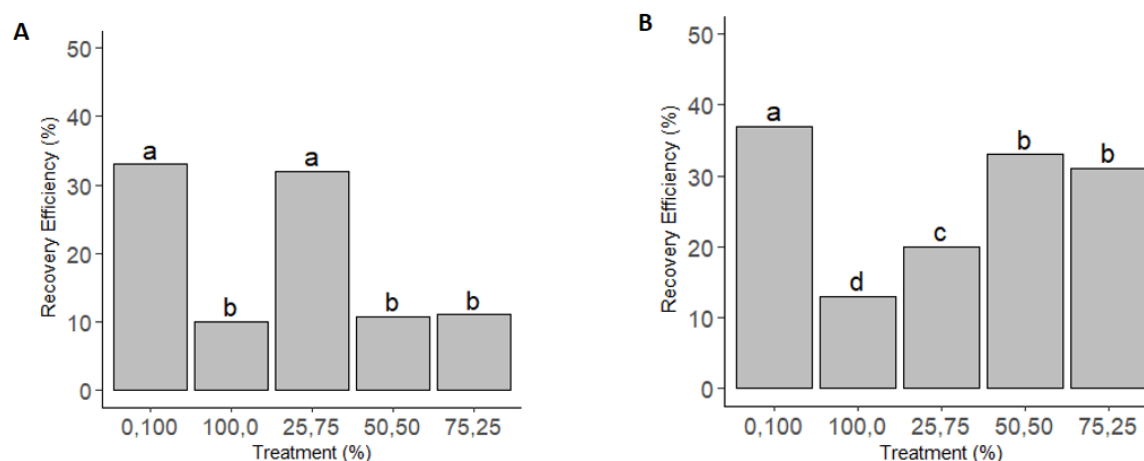


FIGURE 11: A & B is Maize Monocrop and Maize Intercrop Recovery Efficiency Respectively.

Maize monocrop (*Figure 11 a*), 0,100 and 25,75 fertilizer combinations had the highest RE (35%), making them statistically significant. Maize intercrop in (*Figure 11 b*), RE peaked at 0,100 (40%), followed by 50,50 and 75,25 (35%). 100,0 had the lowest RE (15%), while 25,75 was also lower (25%).

IV. DISCUSSION

4.1 Soil Nutrients Dynamics:

Nitrate dynamics varied strongly with fertilizer type. Early-season NO_3^- peaks occurred in inorganic-dominated treatments (25,75 and 0,100) due to rapid urea hydrolysis and nitrification after fertilizer application. These peaks were short-lived, likely due to plant uptake and leaching losses. In contrast, FYM-rich treatments (75,25 and 100,0) maintained moderate, stable NO_3^- levels, reflecting slower N release through mineralization and better synchrony with crop demand. The 50,50 combination balanced rapid mineral N supply with sustained release from FYM, while the control (0,0) had the lowest NO_3^- due to nutrient limitation. These findings agree with (Sahoo et al., 2022), who reported that urea drives early nitrate surges while organic sources buffer N release over time. Cropping systems also influenced nitrate availability. *Desmodium* plots showed consistently lower NO_3^- levels, suggesting efficient uptake through symbiotic N fixation, while intercrops exhibited intermediate levels due to complementary N use between maize and *desmodium*. This supports (Giller & Cadisch, 1995), who noted that cereal-legume intercrops enhance nutrient-use efficiency and reduce nitrate losses.

Ammonium (NH_4^+) levels were significantly affected by cropping system and fertilizer type. FYM-based treatments (100,0 and 75,25) recorded the highest NH_4^+ due to continuous organic N mineralization, while 0,100 and 0,0 had the lowest levels. Balanced treatments (25,75 and 50,50) showed intermediate values, indicating steady N supply from both sources, consistent with (Aboyeji et al., 2019). *Desmodium* and intercrop systems maintained higher NH_4^+ for longer, likely due to reduced nitrification from legume-released inhibitors (Subbarao et al., 2007) and biological N fixation that conserved soil NH_4^+ .

Soil pH responded distinctly to fertilizer type and cropping system. FYM-based treatments maintained higher pH values (6.3-6.5), while plots receiving 100% inorganic N (urea) showed lower pH (around 5.2), consistent with urea-induced acidification during nitrification (M. Zhou et al., 2017). The addition of FYM increased soil pH by supplying base cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+), improving cation exchange capacity (CEC), and promoting microbial CO_2 release that enhances carbonate buffering. Conversely, urea and TSP application increased H^+ concentration through nitrification and phosphate fixation, contributing to soil acidification. A significant interaction between fertilizer regime and cropping system indicated that *desmodium*-based systems buffered soil acidity more effectively than sole maize, likely due to rhizobial activity and higher organic inputs. Across all treatments, pH tended to be slightly lower in deeper layers, reflecting leaching of acidic ions and reduced organic matter influence in subsoil horizons. These results align with (Girma et al., 2020), who reported that organic amendments enhance pH

buffering in acid-prone tropical soils. Throughout the cropping season, a gradual rise in pH coincided with topdressing events, particularly in FYM-amended plots, indicating the alkaline buffering effect of organic inputs. *Desmodium* plots consistently recorded the highest surface pH values, attributed to root exudates and microbial activity that stabilize rhizosphere pH. In contrast, maize plots under high inorganic fertilizer rates (0,100 and 25,75) had the lowest pH, showing stronger acidification effects. The intercrop maintained intermediate values, reflecting nutrient complementarity between maize and *desmodium*.

Fertilizer treatments significantly influenced available phosphorus, indicating enhanced solubilization from FYM through microbial phosphate mobilization (Richardson & Simpson, 2011). Phosphorus levels increased notably in the 020 cm layer, reflecting surface enrichment from fertilizer and organic matter decomposition. The 50,50 and 75,25 treatments consistently recorded the highest available P, attributed to organic acids released during FYM decomposition that dissolve bound phosphates and stimulate microbial mineralization. In contrast, the 0,100 (sole inorganic) plots had the lowest P levels due to phosphate fixation in acidic conditions and the absence of organic chelating agents, while the 0,0 control remained nutrient-depleted. *Desmodium* plots maintained higher available P, likely due to rhizosphere acidification and organic acid exudation (Bhuyan et al., 2020), which mobilized P and enhanced microbial biomass. Intercropping sustained moderate but stable P levels, benefiting from nutrient complementarity between maize and *desmodium* (Jin et al., 2024). Sole maize plots showed faster P decline, reflecting high uptake and limited recycling. Overall, balanced organic-inorganic fertilization (50,50) optimized P availability and uptake efficiency in these highland soils.

Total nitrogen peaked around DAP 150, reflecting active N cycling, root exudation, and microbial activity before declining toward harvest due to crop uptake and potential losses. The 50,50 and 75,25 treatments maintained the highest total N concentrations, attributed to synchronized release where FYM supplied slow-release organic N and inorganic fertilizer provided readily available forms (Palm et al., 2001). In contrast, 0,0 and 0,100 plots recorded the lowest N, the latter declining sharply after DAP 90 due to leaching and rapid plant uptake. *Desmodium* plots consistently exhibited the highest N levels owing to biological nitrogen fixation and enhanced microbial biomass supported by FYM (Freyer & Bingen, 2021). The intercrop maintained stable intermediate N concentrations, benefiting from complementary N acquisition where *desmodium* fixed atmospheric N and maize utilized mineral N (Giller & Cadisch, 1995). Sole maize plots, especially under 0,100, showed sharp declines post-silking due to intensive uptake and low buffering capacity. Overall, integrating FYM with inorganic N (particularly 50,50) sustained higher N availability and improved soil fertility through enhanced microbial cycling and reduced losses.

Soil organic carbon (SOC) showed temporal and spatial variation, with higher values in surface soils (0–20 cm). FYM application significantly increased SOC through additions of both labile fractions that fuel microbial activity and recalcitrant carbon that enhances long-term sequestration and soil structure (Palm et al., 2001). The 50,50 and 75,25 treatments maintained higher SOC, while 0,0 and 0,100 plots had the lowest due to lack of organic input and faster mineralization. *Desmodium* plots recorded the highest SOC, attributed to dense root biomass, nitrogen fixation, and rhizo-deposition that enrich soil organic matter (Drinkwater et al., 1998). The intercrop maintained moderate but stable SOC levels, benefiting from root complementarity and slower decomposition rates under FYM-inclusive regimes (F. Zhang & Li, 2003). Sole maize plots had the lowest carbon due to lower residue return and rapid decomposition. Overall, FYM-based combinations (especially 50,50) improved SOC accumulation, supporting balanced C:N ratios, better mineralization, and long-term fertility in the Keiyo North Nitisols.

4.2 Maize Yield, Biomass, and Nutrient Uptake (N and P):

Maize yield and nutrient uptake in Keiyo North responded strongly to fertilizer type and combination, with FYM-rich treatments performing best overall. The highest yields were recorded under the 50,50, 75,25, and 100,0 fertilizer rates, all statistically comparable, indicating that organic inputs enhanced productivity by improving soil moisture retention and nutrient synchrony. The lowest yield in the 0,0 treatment confirmed nutrient limitations, while the moderate yield under 0,100 reflected the immediate but short-lived nutrient supply from urea without the buffering benefits of FYM. These findings agree with (Kamau et al., 2022), who reported that organic inputs enhance soil resilience and crop yield stability under moisture-limited conditions. In intercrop systems, FYM–inorganic blends produced the highest yields, highlighting improved rhizospheric interactions and biological nitrogen fixation (BNF) by *desmodium*, consistent with (Wanyama et al., 2023), who showed that FYM integration enhances intercrop productivity and land-use efficiency under variable rainfall.

Biomass accumulation followed a similar pattern, with the 50,50 and 75,25 combinations producing the highest values. The strong performance of FYM-inclusive treatments reflects enhanced soil structure, microbial activity, and nutrient availability that support both vegetative and reproductive growth. Lower biomass under 0,0 and 0,100 treatments underscores the limited

water retention and nutrient buffering in the absence of organic matter. The results align with (Mucheru-Muna et al., 2021), who emphasized the synergy between FYM and inorganic N for optimal maize biomass accumulation.

Nitrogen uptake was highest in the 50,50 treatment, confirming the synergistic effect of combining fast-release urea with slow-mineralizing FYM to ensure continuous N supply throughout the season. FYM improved nitrogen use efficiency by enhancing microbial activity and soil aeration, minimizing leaching and volatilization losses. The 100,0 treatment lagged behind, likely due to slow mineralization that failed to meet maize's early N demand. Intercropping further improved N uptake through BNF by *desmodium* and complementary root systems that enhanced N retention and minimized loss pathways, consistent with (J. M. Kihara & Bolo et al., 2021). The pattern supports the findings of (Breure et al., 2023) that partial substitution of urea with FYM increases N uptake efficiency and resilience under fluctuating moisture conditions.

Phosphorus uptake followed similar trends, with the 75,25 and 50,50 treatments showed the highest value in intercrops. The improved uptake reflects FYM's ability to mobilize occluded P through organic acid release and stimulation of microbial P cycling (Jairus et al., 2021). The synergistic effects of *desmodium*'s rhizosphere acidification and FYM-induced mineral dissolution enhanced P availability and plant uptake. In contrast, 0,0 and 0,100 treatments recorded the lowest uptake, reflecting P deficiency and fixation in acidic soils. These results confirm (Arruda et al., 2019), who found that combining organic and inorganic sources optimizes P solubility and root acquisition efficiency.

4.3 Desmodium Yield, and Nutrient Uptake (N and P):

Desmodium yield trends indicate that organic nutrient sources more effectively support its growth. Similar findings by (Kassaw & Alemu et al., 2022) reported improved *Desmodium* yields under balanced nutrient application and favorable microclimatic conditions. However, (J. M. Kihara & Bolo et al., 2021) observed reduced biomass under full FYM due to delayed nutrient release in cooler environments, suggesting site-specific responses.

Nitrogen uptake was generally higher in intercropped *Desmodium* than in sole stands, with the greatest values recorded under the 50,50 and 75,25 treatments. This enhancement is likely associated with improved root nodulation and biological nitrogen fixation (BNF) in intercrops under favorable soil conditions (Ndung'u et al., 2021).

Both sole and intercropped *Desmodium* exhibited high P uptake across fertilizer regimes. Interestingly, even the control (0,0) showed the highest %P concentration in both systems, suggesting that *Desmodium* efficiently acquires P from low-input soils, possibly through root exudates or mycorrhizal associations (Macharia et al., 2020). However, yield-based P uptake was greater under 0,100 and 25,75 treatments, corresponding with higher biomass production in these plots.

4.4 Agronomic and Recovery Efficiency:

In the maize monocrop, AE was highest under the 25,75 and 75,25 fertilizer combinations, followed closely by the 50,50 ratio. The 100,0 treatment recorded the lowest AE, highlighting limited N availability from organic sources alone. All AE values fell within or above the critical benchmark of 15–30 kg kg⁻¹ recommended for smallholder systems (W. Zhang et al., 2016). The strong performance of 25,75 and 75,25 confirms that combining fast-acting inorganic N with a slower-release organic source enhances nutrient synchronization and minimizes leaching losses, consistent with (C. Zhou et al., 2021). In intercrops, AE was highest under 75,25, whereas FYM-only and 0,100 treatments performed poorly, reflecting nutrient imbalances or legume–maize N competition in low-N regimes. The intercrop advantage likely arises from greater root diversity and improved soil nutrient exploration, though high FYM proportions may limit maize N uptake due to *Desmodium*'s early N demand and possible suppression of nitrification (J. M. Kihara & Bolo, 2021).

In the maize monocrop, RE was greatest under the 0,100 and 25,75 fertilizer combinations, significantly outperforming other treatments, while 100,0 and 75,25 recorded the lowest values. The higher RE under mineral N treatments suggests rapid N availability, particularly in drier or cooler conditions, supporting (Bhardwaj et al., 2021), who observed low RE under sole FYM due to delayed mineralization. In the intercrop, RE peaked under 0,100, followed by 50,50 and 75,25, whereas 25,75 and 100,0 showed reduced efficiency. The relatively high RE under 0,100 and 50,50 implies that biological nitrogen fixation (BNF) from *Desmodium* likely supplemented soil N, reducing maize dependence on applied fertilizer and improving overall nutrient use efficiency.

V. CONCLUSION

From this study, it is concluded that: (i) Fertilizer substitutions are important: Combining inorganic N with FYM, especially at 50,50 or 25,75, improved nutrient uptake, maize and *desmodium* biomass yields. (ii) The cropping system influences outcomes:

Intercropping maize with *desmodium* increased N uptake compared to sole maize, due to better root interactions and nitrogen fixation. Based on the above findings, the following recommendations are made: (i) Implement integrated nutrient management strategies, particularly 50,50, 75,25 and FYM-inorganic combinations, for maize and *desmodium* cropping systems they reliably enhance yields, nutrient use efficiencies, and lower emission intensities. (ii) Promote maize-desmodium intercropping in ASALs and other smallholder systems, especially where nitrogen fixation and erosion control are important. This intercropping method has shown agronomic and environmental advantages over monocropping.

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