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# Influence of Integrated Nutrient Management and Mulching on Fertilizer Use Efficiency Metrics and Yield Response of Dolichos Bean (*Lablab purpureus* L.) in Semi-Arid Areas of Nakuru County, Kenya

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## Abstract

Efficient use of applied nutrients is essential for improving crop yield, particularly in low-fertility, moisture-limited environments. Fertilizer use efficiency metrics such as Agronomic Use Efficiency (AUE), Partial Factor Productivity (PFP), Yield Response (YR), and Relative Yield (RY) provide important insights into how effectively nutrients are converted into economic yield. These indices help to quantify the contribution of fertilizer inputs to yield improvement and assess the performance of different nutrient management strategies. Evaluating the metrics is critical for identifying practices that enhance productivity while optimizing input use in Dolichos bean production systems. Field experiments were conducted in Maai Mahiu (1˚1'17.2'' S, 36˚35'11.5'' E) and Lare (0˚25'45.2'' S, 36˚03'06.0'' E) Nakuru county, over two seasons (September 2024-January 2025) and (April 2025-August 2025) to evaluated the effect of integrated nutrient management and mulching on Dolichos bean yield and fertilizer use efficiency. Treatments included three rates of NPK 17:17:17 (0, 75, 150 kg ha$^{-1}$), four rates of organic fertilizer (Griincom 2% N:4% P:5% K), 0, 200, 400, 600 kg ha$^{-1}$ applied as dry matter, and two mulch levels of dry wheat straw (with mulch, without mulch). The highest AUE in Lare was observed in season 2 (382.93 kg kg$^{-1}$ N) was recorded under 75 kg ha$^{-1}$ NPK + 600 kg ha$^{-1}$ organic fertilizer with mulch, while in Maai Mahiu the highest value (340.04 kg kg$^{-1}$ N) was recorded under 0 kg ha$^{-1}$ NPK + 200 kg ha$^{-1}$ organic fertilizer with mulch in season 1. The highest PFP (468.24 kg kg$^{-1}$ N ha$^{-1}$) was observed at Lare season 2 under 200 kg organic fertilizer with mulch and no NPK, while the maximum RY (2495.13 kg ha$^{-1}$) occurred under 150 kg ha$^{-1}$ NPK + 600 kg ha$^{-1}$ organic fertilizer with mulch at Lare season 1. The greatest YR (738.97%) was recorded at Maai Mahiu season 1 under the same treatment (150 kg ha$^{-1}$ NPK + 600 kg ha$^{-1}$ organic fertilizer with mulch). Mulching enhanced soil moisture retention and nutrient uptake, improving efficiency across sites. Economically, moderate N combined with organic fertilizer and mulch provided high yield per unit of nutrient applied, highlighting INM as a sustainable and cost-effective strategy for Dolichos bean production in semi-arid environments.

## Keywords

Dolichos Bean, Fertilizer Use Efficiency, Agronomic Use Efficiency, Partial Factor Productivity, Yield Response, Relative Yield, Yield

## 1. Introduction

Efficient use of fertilizers is a cornerstone of sustainable crop production, particularly for smallholder farmers where input costs are high and soils are often nutrient-poor [1]. Fertilizer use efficiency (FUE) metrics. Agronomic Use Efficiency (AUE), Partial Factor Productivity (PFP), Relative Yield (RY) and Yield Response (YR); provide quantitative measures of how effectively crops convert applied nutrients into economic yield [2]. These metrics are essential for identifying management strategies that maximize yield per unit of fertilizer, inform nutrient recommendations, and reduce nutrient losses to the environment [2]. In sub-Saharan Africa, fertilizer use remains well below global averages, yet even modest increases, when managed appropriately, can substantially improve productivity and efficiency.

Dolichos lablab (*Lablab purpureus* L.) is a drought-tolerant legume that contributes both to food security and soil fertility improvement through biological nitrogen fixation [3]. Like other legumes, lablab exhibits unique nutrient acquisition strategies that influence its response to fertilizer inputs, making fertilizer use efficiency assessment particularly important. Studies on other grain legumes have demonstrated that integrated application of organic amendments and mineral fertilizers improves nutrient availability, biological nitrogen fixation, grain yield, and soil fertility compared with sole nutrient sources [4]. Similar benefits have been reported in soybean, where integrated nutrient management improved productivity and nutrient-use efficiency under smallholder farming [5].

Integrated Soil Fertility Management (ISFM), which combines inorganic fertilizers with organic inputs and improved soil management practices, has been widely recommended for East African smallholder farmers due to its ability to enhance nutrient cycling and crop response [6]. Studies in Kenya's central highlands show high adoption of organic amendments alongside inorganic fertilizers, reflecting farmer recognition of their complementary roles in improving soil fertility [7]. Fertilizer use efficiency metrics derived from such integrated practices provide insights into how effectively lablab converts added nutrients into biomass and grain yield under the moisture- and nutrient-limited conditions typical of smallholder farms. AUE measures the additional yield gained per unit of nutrient applied, PFP reflects yield per unit of fertilizer input, and RY indicates the proportion of maximum potential yield achieved, metrics critical for evaluating the cost-effectiveness and sustainability of nutrient management strategies [8].

Despite growing evidence that integrated nutrient management can improve crop productivity and soil fertility [6]. Most previous studies have focused primarily on yield responses and soil fertility outcomes, with little attention given to quantifying efficiency indices [5] [9]. Consequently, there is insufficient understanding of how integrated organic and inorganic fertilizer strategies influence nutrient-use efficiency and yield performance in Dolichos bean under varying environmental conditions. This knowledge gap limits the development of site-specific nutrient management recommendations that can maximize productivity while enhancing resource-use efficiency and environmental sustainability. Therefore, this study evaluated the effects of integrated organic and inorganic fertilizer management on grain yield and fertilizer use efficiency indices (AUE, PFP, RY, and YR) of Dolichos bean under contrasting site and seasonal conditions. It was hypothesized that combined application of organic and inorganic fertilizers would result in higher grain yield and fertilizer use efficiency than sole fertilizer applications or unfertilized controls due to improved nutrient availability and enhanced soil fertility.

## 2. Materials and Methods

### 2.1. Experimental Sites

The experiment was conducted on farm at two sites in Nakuru County representing distinct agro-ecological conditions typical of smallholder farming systems in Kenya: Maai Mahiu ward (1˚01'17.2" S, 36˚35'11.5" E) in Naivasha Sub-County and Lare ward (0˚25'45.2" S, 36˚03'06.0" E) in Njoro Sub-County. Both sites experience bimodal rainfall, with long rains occurring between March and May and short rains between October and December. Maai Mahiu receives annual rainfall ranging from 443 - 939 mm, with mean temperatures of 25.9˚C - 29.3˚C. Lare receives 600 - 1000 mm of rainfall annually and has temperatures ranging from 24˚C - 30˚C [10] (**Figure 1**).

### 2.2. Experimental Design and Treatments

The experiment was laid out in a 4 × 3 × 2 factorial arrangement using a Randomized Complete Block Design (RCBD) with three replications. The study evaluated the integrated effects of organic fertilizer, inorganic NPK fertilizer (17:17:17), and wheat straw mulch on Dolichos bean (DL 1002). Organic fertilizer (Griincom, N—2%, K—4%, K—5%) was applied on a dry matter basis at four rates (0, 200, 400, and 600 kg ha$^{-1}$), NPK fertilizer at three rates (0, 75, and 150 kg ha$^{-1}$), and dry wheat straw mulch at two levels (mulched and non-mulched). All treatment combinations were randomized within each block. A determinate variety of Dolichos bean, characterized by early maturity, was used. Certified seeds were sourced from Kenya Agricultural and Livestock Research Organization (KALRO) Katumani. Organic mulch of wheat straw was applied uniformly at 5 kg per plot, translating to 11.6 t ha$^{-1}$. Both the organic and inorganic fertilizers were obtained from accredited stockiest in Nakuru City and were denoted as "G" (Griincom organic) and "N" (inorganic NPK) for treatment identification.

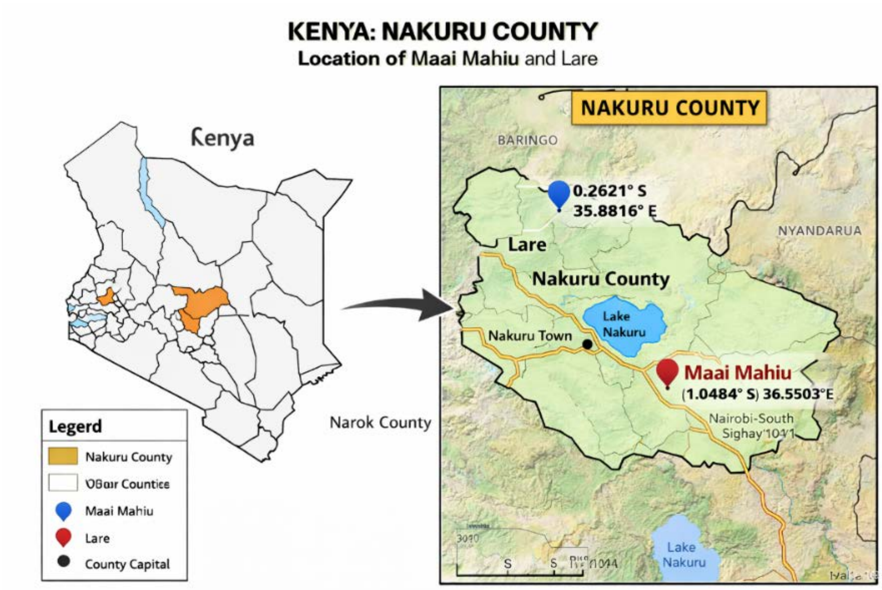


**Figure 1.** Experimental sites. (Source self).

## 2.3. Crop Management and Plot Establishment

Dolichos lablab was established in plots measuring 1.8 m × 2.4 m, with an inter-row spacing of 60 cm and inter-plant spacing of 30 cm, resulting in 32 plants per plot. Two seeds were sown per hole at a seed rate of 25 kg ha$^{-1}$ at the onset of the rainy season and thinned to one seedling per hole one week after emergence. Each plot was bordered by two guard rows on either side, with 0.5 m paths between plots, 1 m between replicates, and a 2 m buffer from the farm edges. Organic manure was applied and incorporated into the soil two weeks before sowing, while NPK 17:17:17 fertilizer was incorporated during sowing. Wheat straw mulch was applied to mulched treatments after emergence to ensure uniform soil surface coverage. Weed control for mulched treatments was carried out manually by hand-uprooting, while non-mulched treatments were hand-weeded two weeks after emergence, and plots were maintained weed-free throughout the growing seasons. Pests were managed using recommended bio-pesticides.

## 2.4. Data Collection

Fertilizer use efficiency of Dolichos lablab was evaluated using Agronomic Use Efficiency (AUE), Partial Factor Productivity (PFP), and Relative Yield (RY). Grain yield per plot was measured at harvest and converted to kg ha$^{-1}$. The amounts of nutrients applied through organic and inorganic fertilizers were recorded. FUE metrics were calculated using standard formulas independently for mulched and non-mulched treatments.

**Agronomic Use Efficiency (AUE)**

AUE measures the additional crop yield obtained per unit of nutrient applied. It reflects how a crop converts applied fertilizer into economic yield. AUE was calculated as

$$\text{AUE} = \frac{Y_f - Y_0}{F},$$

($Y_f$) = grain yield (kg ha$^{-1}$) of the fertilized treatment.

($Y_0$) = grain yield (kg ha$^{-1}$) of the unfertilized control treatment (0 NPK + 0 organic fertilizer) within the same site, season, and mulch level.

($F$) = amount of nitrogen applied (kg ha$^{-1}$).

**Partial Factor Productivity (PFP)**

Partial Factor Productivity (PFP) measures the total grain yield produced per unit of nutrient applied and provides an overall indicator of nutrient productivity. PFP was calculated as:

$$\text{PFP} = \frac{Y_f}{F},$$

($Y_f$) = grain yield (kg ha$^{-1}$) of the fertilized treatment.

($F$) = amount of nutrient applied (kg ha$^{-1}$).

**Relative Yield (RY)**

Relative Yield (RY) expresses the yield achieved by a treatment as a percentage of the maximum yield attained within the same experimental environment. It was calculated as

$$\text{RY} = \frac{Y_t}{Y_m} \times 100$$

($Y_t$) = grain yield (kg ha$^{-1}$) of the treatment.

($Y_m$) = maximum grain yield (kg ha$^{-1}$) recorded among all treatments within the same site, season, and mulch level.

**Yield Response (YR)**

Yield response refers to the increase in crop yield obtained due to application of a treatment compared with the untreated control. It is used to quantify how strongly a crop responds to an intervention and helps evaluate treatment effectiveness in agronomic studies

where:

$$\text{Yield Response}(\%) = \frac{Y_t - Y_0}{Y_0} \times 100$$

where:

($Y_f$) = grain yield (kg ha$^{-1}$) of the fertilized treatment; and

($Y_0$) = grain yield (kg ha$^{-1}$) of the unfertilized control treatment (0 NPK + 0 organic fertilizer) within the same site, season, and mulch level.

**Grain yield (kg ha$^{-1}$)**

Grain yield (kg ha$^{-1}$) was estimated as the product of the number of plants per plot, average number of pods per plant, average number of seeds per pod, and individual seed weight (obtained from the 100-seed weight), divided by the net harvested plot area and converted to a per-hectare basis.

$$\text{Grain Yield}(\text{kg/ha}) = \frac{N_p \times P_p \times S_p \times W_{100} \times 10000}{100 \times A_p \times 1000}$$

$N_p$ = Number of plants per plot.

$P_p$ = Pods per plant.

$S_p$ = Seeds per pod.

$W_{100}$ = 100-seed weight (g).

$A_p$ = Plot area (m$^2$).

## 2.5. Calculation of Total Nitrogen (N kg ha$^{-1}$)

Table 1. The total nitrogen applied (kg N ha$^{-1}$) calculated from both NPK (17:17:17) fertilizer and Griincom organic fertilizer (2% N, 4% P, and 5% K).

| Fertilizer Treatment | Nitrogen Applied (Kg N ha$^{-1}$) |
|---|---|
| N 0, G 0 | 0 |
| N 0, G 200 | 4 |
| N 0, G 400 | 8 |
| N 0, G 600 | 12 |
| N 75, G 0 | 12.75 |
| N 75, G 200 | 16.75 |
| N 75, G 400 | 20.75 |
| N 75, G 600 | 24.75 |
| N 150, G 0 | 25.5 |
| N 150, G 200 | 29.5 |
| N 150, G 400 | 33.5 |
| N 150, G 600 | 37.5 |

Fertilizer use efficiency indices were calculated using the total nitrogen supplied from both NPK (17:17:17) and Griincom organic fertilizer (2% N, 4% P, and 5% K). The nitrogen contribution from each fertilizer source was determined based on its nitrogen concentration and application rate, and the values were summed to obtain the total nitrogen input (kg N ha$^{-1}$) for each treatment. Agronomic Use Efficiency (AUE) was calculated as the increase in grain yield above the unfertilized control per unit of nitrogen applied, while Partial Factor Productivity (PFP) was computed as grain yield per unit of total nitrogen applied. Relative Yield (RY) and Yield Response (YR) were calculated using the corresponding unfertilized control within the same mulch treatment, site, and season. Efficiency metrics were expressed on a nitrogen basis because nitrogen is generally the primary yield-limiting nutrient in the study environments and provides a common unit for comparing fertilizer treatments that combined both inorganic and organic nutrient sources. Nitrogen was used as the reference; nutrient fertilizer efficiency indices such as AUE and PFP are commonly expressed on an N basis in agronomic studies, allowing comparison with published literature and across nutrient management strategies (Table 1).

$$\text{Total N}\left(\text{kg}\cdot\text{ha}^{-1}\right)=\left(\frac{\%N_{\text{NPK}}}{100}\times\text{Rate}_{\text{NPK}}\right)+\left(\frac{\%N_{\text{Organic}}}{100}\times\text{Rate}_{\text{Organic}}\right)$$

where:

- $\%N_{\text{NPK}}=17\%$.
- $\%N_{\text{Organic}}=2\%$.

Rates are expressed in kg ha$^{-1}$.

## 2.6. Data Analysis and Experimental Model

Data collected were checked for normality and homogeneity of variance using the Shapiro-Wilk and Levene's tests, respectively [11]. were first subjected to site- and season-specific analysis of variance (ANOVA) to evaluate treatment effect within each environment and season. Thereafter, a combined ANOVA across sites and seasons was conducted to evaluate interaction effects and overall treatment performance. Analysis was done using a three-factor factorial ANOVA in a Randomized Complete Block Design (RCBD) with three replications. Mean separation for significantly different treatments was conducted using Tukey's Honest Significant Difference (HSD) test at a 5% probability level. Data were analysed entirely using R software version 4.4. 3 [11]. Results were summarized in tables and bar charts showing means, standard errors, and significance levels. The statistical model used was. The statistical model used was

$$\begin{aligned}Y_{ijkl}&=\mu+B_i+G_j+N_k+M_l+\left(G\times N\right)_{jk}+\left(G\times M\right)_{jl}\\&\quad+\left(N\times M\right)_{kl}+\left(G\times N\times M\right)_{jkl}+\epsilon_{ijkl}\end{aligned}$$

where:

$Y_{ijkl}$ = observed response of growth or yield parameter in the *l*-th plot of the *i*-th block with treatment combination of *G*, *N*, and *M*.

$\mu$ = overall mean.

$B_i$ = effect of the $i^{\text{th}}$ block.

$G_j$ = effect of the $j^{\text{th}}$ level of organic fertilizer.

$N_k$ = effect of the $k^{\text{th}}$ level of inorganic fertilizer.

$M_l$ = effect of the $l^{\text{th}}$ level of mulch.

Two-way interactions: $\left(G\times N\right)_{jk},\left(G\times M\right)_{jl},\left(N\times M\right)_{kl}$.

Three-way interaction: $\left(G\times N\times M\right)_{jkl}$.

$\epsilon_{ijkl}$ = random error, assumed normally and independently distributed with mean zero and constant variance ($\sigma^2$).

## 3. Results

Efficient nutrient management is essential for maximizing crop productivity while minimizing input costs, particularly in smallholder farming systems. Dolichos responds to both organic and inorganic fertilizers, and soil management practices such as mulching can enhance nutrient availability and uptake. This section evaluated the effects of NPK and organic fertilizer combinations with mulch on key efficiency and yield metrics: Agronomic Use Efficiency (AUE), Partial Factor Productivity (PFP), Relative Yield (RY), and Yield Response (YR) at two sites and two seasons. These metrics directly address the study's objective of evaluating how different nutrient management strategies influence crop performance and economic returns, providing actionable insights for sustainable crop productivity, including Dolichos production.

### 3.1. Agronomic Use Efficiency (AUE) kg/N

Agronomic use efficiency was significantly affected by fertilizer treatment, mulch application, site, and season. Significant treatment—site and treatment—mulch interactions were also observed, indicating that the response of AUE to fertilizer management varied across environments and mulch conditions as shown in Table 2 below. At Lare in season 1, the highest AUE 178.78 kg grain $kg^{-1}$ N, was recorded at 0 kg $ha^{-1}$ NPK + 400 kg $ha^{-1}$ organic fertilizer with mulch, followed by 147.73 kg $kg^{-1}$ N under 0 kg $ha^{-1}$ NPK + 600 kg $ha^{-1}$ organic fertilizer with mulch and 142.58 kg $kg^{-1}$ N under 75 kg $ha^{-1}$ NPK without organic fertilizer but with mulch. In contrast, the lowest AUE 36.55 kg $kg^{-1}$ N, occurred at 75 kg $ha^{-1}$ NPK + 600 kg $ha^{-1}$ organic fertilizer with mulch, indicating reduced efficiency at higher nutrient inputs. At Maai Mahiu season 1, AUE values were generally higher than at Lare. The highest value 340.04 kg $kg^{-1}$ N, was recorded at 0 kg $ha^{-1}$ NPK + 200 kg $ha^{-1}$ organic fertilizer with mulch, followed by 283.51 kg $kg^{-1}$ N under 0 kg $ha^{-1}$ NPK + 200 kg $ha^{-1}$ organic fertilizer without mulch. Conversely, the lowest AUE 56.80 kg $kg^{-1}$ N, occurred under 75 kg $ha^{-1}$ NPK + 600 kg $ha^{-1}$ organic fertilizer without mulch, suggesting that excessive nutrient application reduced nutrient use efficiency. During season 2, AUE values showed a similar trend but with some variation across treatments. At Lare season 2, the highest value 382.93 kg $kg^{-1}$ N, was recorded at 75 kg $ha^{-1}$ NPK + 600 kg $ha^{-1}$ organic fertilizer with mulch, followed by 204.06 kg $kg^{-1}$ N under 0 kg $ha^{-1}$ NPK + 400 kg $ha^{-1}$ organic fertilizer with mulch. The lowest value 40.12 kg $kg^{-1}$ N, was observed at 150 kg $ha^{-1}$ NPK + 400 kg $ha^{-1}$ organic fertilizer with mulch. At Maai Mahiu season 2, the highest AUE 107.91 kg $kg^{-1}$ N, was recorded under 75 kg $ha^{-1}$ NPK without organic fertilizer but with mulch, followed by 99.68 kg $kg^{-1}$ N under 0 kg $ha^{-1}$ NPK + 200 kg $ha^{-1}$ organic fertilizer without mulch. The lowest value 27.09 kg $kg^{-1}$ N, occurred at 75 kg $ha^{-1}$ NPK + 600 kg $ha^{-1}$ organic fertilizer without mulch, indicating reduced efficiency under high fertilizer rates. Treatments integrating with ≤75 kg $ha^{-1}$ NPK fertilizer inputs with organic fertilizer (200 - 400 kg $ha^{-1}$) and mulch tended to produce higher AUE values, while excessive fertilizer rates often resulted in reduced nutrient use efficiency.

**Table 2.** Mean values for agronomic use efficiency for Dolichos crop as affected by integrated nutrient management and mulching application at Lare and Maai Mahiu Nakuru County Kenya during season 1 (September 2024-January 2025) and season 2 (April-August 2025).

| Treatments | | | | | | |
|---|---|---|---|---|---|---|
| NPK (Kg/Ha) | Organic Fertilizer (Kg/Ha) | Organic Mulch | Lare S1 | Maai Mahiu S1 | Lare S2 | Maai Mahiu S2 |
| 0 | 200 | $M_0$ | 74.36[bcd] | 283.51[a] | 79.17[e] | 99.68[a] |
| | 400 | $M_0$ | 55.09[cd] | 139.79[bcd] | 60.84[e] | 47.87[bcd] |
| | 600 | $M_0$ | 129.84[abc] | 134.15[bcde] | 129.25[cd] | 72.87[abcd] |
| | 200 | $M_1$ | 71.91[bcd] | 340.04[a] | 63.26[e] | 94.09[ab] |
| | 400 | $M_1$ | 178.78[a] | 177.63[b] | 204.06[b] | 54.65[abcd] |
| | 600 | $M_1$ | 147.73[ab] | 153.06[bc] | 150.23[c] | 71.07[abcd] |
| 75 | 0 | $M_0$ | 78.63[bcd] | 110.67[bcdefg] | 81.18[e] | 53.00[abcd] |
| | 200 | $M_0$ | 79.89[bcd] | 86.42[cdefg] | 83.85[e] | 42.53[cd] |
| | 400 | $M_0$ | 101.20[bcd] | 91.52[cdefg] | 100.30[cde] | 56.10[abcd] |
| | 600 | $M_0$ | 104.10[bcd] | 56.80[g] | 106.53[cde] | 27.09[d] |
| | 0 | $M_1$ | 142.58[ab] | 185.1[b] | 139.18[cd] | 107.91[a] |
| | 200 | $M_1$ | 122.87[abc] | 130.09[bcdef] | 118.76[cd] | 71.36[abcd] |
| | 400 | $M_1$ | 107.62[abcd] | 118.93[bcdefg] | 106.46[cde] | 71.52[abcd] |
| | 600 | $M_1$ | 36.55[d] | 83.85[defg] | 382.93[a] | 44.09[cd] |
| 150 | 0 | $M_0$ | 63.89[cd] | 69.11[efg] | 64.79[e] | 40.28[d] |
| | 200 | $M_0$ | 106.96[bcd] | 132.88[bcde] | 106.03[cde] | 81.83[abc] |
| | 400 | $M_0$ | 55.68[cd] | 67.04[efg] | 58.40[ef] | 45.08[cd] |
| | 600 | $M_0$ | 57.00[cd] | 64.57[fg] | 59.81[e] | 44.96[cd] |
| | 0 | $M_1$ | 85.02[bcd] | 75.31[defg] | 79.14[e] | 36.73[d] |
| | 200 | $M_1$ | 80.42[bcd] | 91.36[cdefg] | 79.72[e] | 58.02[abcd] |
| | 400 | $M_1$ | 39.37[d] | 78.30[defg] | 40.12[ef] | 48.92[bcd] |
| | 600 | $M_1$ | 66.54[bcd] | 79.17[defg] | 65.09[e] | 52.93[abcd] |
| HSD (0.05) | | | 1.97 | 5.07 | 6.86 | 10.61 |

Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ according to Tukey's HSD test. (S1—season 1, S1—season 2, $M_0$—without mulch, $M_1$—with mulch).

Mulching generally improved agronomic use efficiency across most fertilizer treatments and sites. At Lare season 1, AUE increased from 55.09 kg kg$^{-1}$ N ha$^{-1}$ without mulch to 178.78 kg kg$^{-1}$ N ha$^{-1}$ with mulch under 0 kg ha$^{-1}$ NPK + 400 kg ha$^{-1}$ organic fertilizer. Similarly, at Maai Mahiu season 1, AUE increased from 283.51 kg kg$^{-1}$ N ha$^{-1}$ without mulch to 340.04 kg kg$^{-1}$ N ha$^{-1}$ with mulch at 0 kg ha$^{-1}$ NPK + 200 kg ha$^{-1}$ organic fertilizer. A similar pattern was observed in season 2, where mulched treatments generally recorded higher AUE values. At Lare season 2, at 0 kg ha$^{-1}$ NPK + 400 kg ha$^{-1}$ organic fertilizer recorded 204.06 kg kg$^{-1}$ N ha$^{-1}$ with mulch compared with 60.84 kg kg$^{-1}$ N ha$^{-1}$ without mulch. Likewise, at Maai Mahiu season 2, 75 kg ha$^{-1}$ NPK without organic fertilizer recorded 107.91 kg kg$^{-1}$ N ha$^{-1}$ with mulch, compared with 53.00 kg kg$^{-1}$ N ha$^{-1}$ without mulch. Mulching enhanced agronomic use efficiency by improving soil moisture retention and nutrient availability, thereby facilitating better nutrient uptake and utilization by the crop.

Across the sites, Maai Mahiu season 1 generally recorded higher AUE values than Lare season 1, with the highest value reaching 340.04 kg kg$^{-1}$ N ha$^{-1}$, at (0 kg ha$^{-1}$ NPK + 200 kg ha$^{-1}$ organic fertilizer with mulch) compared with 178.78 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 under (0 kg ha$^{-1}$ NPK + 400 kg ha$^{-1}$ organic fertilizer with mulch $M_1$). However, during season 2, Lare recorded the highest overall AUE value (382.93 kg kg$^{-1}$ N ha$^{-1}$) under 75 kg ha$^{-1}$ NPK + 600 kg ha$^{-1}$ organic fertilizer with mulch, indicating improved nutrient utilization during season 2. In contrast, Maai Mahiu season 2 recorded relatively lower AUE values, with a maximum of 107.91 kg kg$^{-1}$ N ha$^{-1}$ (75 kg ha$^{-1}$ NPK without organic, with mulch). Both site and seasonal conditions influenced agronomic nitrogen use efficiency, although the integration of organic fertilizer and mulch consistently improved AUE across sites and seasons.

### 3.2. Partial Factor Productivity (PFP) Kg N$^{-1}$

The results shown in **Table 3** below, Partial Factor Productivity (PFP) was significantly influenced by fertilizer treatment, mulch application, site, and season. Significant interaction effects were also observed, indicating that the response of PFP to integrated nutrient management varied across locations and growing seasons. These results demonstrate that nutrient productivity was strongly dependent on both fertilizer combinations and environmental conditions. Across both Lare and Maai Mahiu sites, the highest PFP values were generally recorded in treatments that involved organic fertilizer combined with mulch but without mineral fertilizer application. Under treatment with 0 kg ha$^{-1}$ N and 200 kg ha$^{-1}$ organic fertilizer with mulch produced the highest PFP values at both sites and seasons, recording 400.79 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1, 94.09 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 1, 468.24 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, and 340.04 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 2. Similarly, the treatment with 0 kg ha$^{-1}$ NPK and 400 kg ha$^{-1}$ organic fertilizer with mulch also resulted in relatively high PFP values of 362.22 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1, 54.65 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 1, 425.54 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, and 177.63 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 2. In contrast, treatments involving higher mineral fertilizer rates (150 kg NPK ha$^{-1}$) consistently produced lower PFP values across both sites and seasons. At the treatment combining 150 kg ha$^{-1}$ NPK with 400 kg ha$^{-1}$ organic fertilizer without mulch recorded very low PFP values of 87.15 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1, 45.08 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 1, 92.08 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, and

67.04 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 2. Similarly, the treatment with 150 kg ha$^{-1}$ N and 600 kg ha$^{-1}$ organic fertilizer without mulch recorded 85.33 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1, 44.96 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 1, 89.90 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, and 64.57 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 2. Treatments with 75 kg NPK ha$^{-1}$ produced intermediate PFP values. Under treatment with 75 kg ha$^{-1}$ NPK and mulch without organic fertilizer recorded 257.87 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1, 107.86 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 1, 278.67 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, and 185.33 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 2. However, when higher organic fertilizer levels were added to this nitrogen rate, PFP values generally declined, particularly in the treatment with 75 kg ha$^{-1}$ NPK and 600 kg ha$^{-1}$ organic fertilizer without mulch, which recorded 146.21 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1, 27.15 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 1, 152.11 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, and 56.81 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 2. Increasing fertilizer input rates did not necessarily improve nutrient productivity, and nutrient use efficiency tended to decline when high fertilizer rates were applied. Instead, moderate organic fertilizer inputs combined with mulch resulted in higher nutrient productivity across both study sites.

Mulching generally improved Partial Factor Productivity across both sites and seasons, although the magnitude of the effect varied depending on fertilizer combinations. Across the treatments without mineral fertilizer, the presence of mulch significantly increased PFP. The treatment with 200 kg ha$^{-1}$ organic fertilizer without mulch ($M_0$) recorded 338.30 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 and 361.23 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, while the same treatment with mulch increased PFP to 400.79 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 and 468.24 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2. At Maai Mahiu, the same treatments produced 99.68 kg kg$^{-1}$ N ha$^{-1}$ and 283.51 kg kg$^{-1}$ n ha$^{-1}$ without mulch, compared with 94.09 kg kg$^{-1}$ N ha$^{-1}$ and 340.04 kg kg$^{-1}$ N ha$^{-1}$ with mulch in seasons 1 and 2, respectively. Similarly, the treatment with 400 kg ha$^{-1}$ organic fertilizer without mulch produced 187.06 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 and 201.87 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, whereas the addition of mulch increased PFP to 362.22 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 and 425.54 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2. At Maai Mahiu, the same treatments recorded 47.87 kg kg$^{-1}$ N ha$^{-1}$ and 139.79 kg kg$^{-1}$ N ha$^{-1}$ without mulch, compared with 54.65 kg kg$^{-1}$ N ha$^{-1}$ and 177.63 kg kg$^{-1}$ N ha$^{-1}$ with mulch. The beneficial effect of mulch was also observed in treatments involving mineral fertilizer. Under the treatment with 75 kg ha$^{-1}$ NPK without organic fertilizer recorded 161.33 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 and 169.67 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2 without mulch, but increased to 257.87 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 and 278.67 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2 when mulch was applied. At Maai Mahiu, the same treatment increased from 53.00 kg kg$^{-1}$ N ha$^{-1}$ and 110.67 kg kg$^{-1}$ N ha$^{-1}$ without mulch to 107.86 kg kg$^{-1}$ N ha$^{-1}$ and 185.33 kg kg$^{-1}$ N ha$^{-1}$ with mulch. The improvements in PFP indicate that mulch enhanced nutrient use efficiency, reducing soil moisture loss, improving soil temperature regulation, minimizing nutrient leaching, and enhancing microbial activity, all of which contribute to improved nutrient uptake by crops.

**Table 3.** Mean values for partial factor productivity for Dolichos crop as affected by integrated nutrient management and mulching application at Lare and Maai Mahiu Nakuru County Kenya during season 1 (September 2024-January 2025) and season 2 (April-August 2025).

| Treatments | | | | | | |
|---|---|---|---|---|---|---|
| NPK (Kg/Ha) | Organic Fertilizer (Kg/Ha) | Organic Mulch | Lare S1 | Maai Mahiu S1 | Lare S2 | Maai Mahiu S2 |
| 0 | 200 | $M_0$ | 338.30$^{ab}$ | 99.68$^{a}$ | 361.23$^{ab}$ | 283.51$^{a}$ |
| | 400 | $M_0$ | 187.06$^{cdef}$ | 47.87$^{bcd}$ | 201.87$^{bc}$ | 139.79$^{bcd}$ |
| | 600 | $M_0$ | 217.82$^{cd}$ | 72.87$^{abcd}$ | 223.27$^{bc}$ | 134.15$^{bcde}$ |
| | 200 | $M_1$ | 400.79$^{a}$ | 94.09$^{ab}$ | 468.24$^{a}$ | 340.04$^{a}$ |
| | 400 | $M_1$ | 362.22$^{ab}$ | 54.65$^{abcd}$ | 425.54$^{a}$ | 177.63$^{b}$ |
| | 600 | $M_1$ | 270.03$^{bc}$ | 71.07$^{abcd}$ | 297.88$^{b}$ | 153.06$^{bc}$ |
| 75 | 0 | $M_0$ | 161.33$^{cdef}$ | 53.00$^{abcd}$ | 169.67$^{cd}$ | 110.67$^{bcdefg}$ |
| | 200 | $M_0$ | 142.94$^{def}$ | 42.49$^{cd}$ | 151.40$^{cd}$ | 86.43$^{cdefg}$ |
| | 400 | $M_0$ | 151.60$^{def}$ | 56.14$^{abcd}$ | 154.67$^{cd}$ | 91.54$^{cdefg}$ |
| | 600 | $M_0$ | 146.21$^{def}$ | 27.15$^{d}$ | 152.11$^{cd}$ | 56.81$^{g}$ |
| | 0 | $M_1$ | 257.87$^{bc}$ | 107.86$^{a}$ | 278.67$^{b}$ | 185.33$^{b}$ |
| | 200 | $M_1$ | 210.70$^{cde}$ | 71.36$^{abcd}$ | 224.66$^{bc}$ | 130.09$^{bcdef}$ |
| | 400 | $M_1$ | 178.51$^{cdef}$ | 71.52$^{abcd}$ | 191.85$^{bc}$ | 118.93$^{bcdefg}$ |
| | 600 | $M_1$ | 95.90$^{ef}$ | 43.88$^{cd}$ | 454.89$^{a}$ | 83.84$^{defg}$ |
| 150 | 0 | $M_0$ | 105.16$^{def}$ | 40.28$^{d}$ | 109.04$^{cd}$ | 69.11$^{efg}$ |
| | 200 | $M_0$ | 182.39$^{cdef}$ | 81.80$^{abc}$ | 194.90$^{bc}$ | 133.00$^{bcde}$ |
| | 400 | $M_0$ | 87.15$^{f}$ | 45.08$^{cd}$ | 92.08$^{cd}$ | 67.04$^{efg}$ |
| | 600 | $M_0$ | 85.33$^{f}$ | 44.96$^{cd}$ | 89.90$^{cd}$ | 64.57$^{fg}$ |
| | 0 | $M_1$ | 142.56$^{def}$ | 36.66$^{d}$ | 148.89$^{cd}$ | 75.31$^{defg}$ |
| | 200 | $M_1$ | 129.82$^{def}$ | 58.34$^{abcd}$ | 139.78$^{cd}$ | 91.37$^{cdefg}$ |
| | 400 | $M_1$ | 83.17$^{f}$ | 48.92$^{bcd}$ | 93.01$^{cd}$ | 78.30$^{defg}$ |
| | 600 | $M_1$ | 105.67$^{def}$ | 52.93$^{abcd}$ | 112.33$^{cd}$ | 79.17$^{defg}$ |
| HSD (0.05) | | | 8.80 | 3.59 | 5.28 | 5.08 |

Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ according to Tukey's HSD test. (S1—season 1, S1—season 2, $M_0$—without mulch, $M_1$—with mulch).

Seasonal and site variations in PFP were observed across the treatments. Across most treatments, Lare consistently recorded higher PFP values than Maai Mahiu. The treatment with 200 kg ha$^{-1}$ organic fertilizer without mulch produced 338.30 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 compared with 99.68 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 1, and 361.23 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2 compared with 283.51 kg kg$^{-1}$ N ha$^{-1}$ at Maai Mahiu season 2. Similarly, the treatment with 400 kg ha$^{-1}$ organic fertilizer with mulch recorded 362.22 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 1 and 425.54 kg kg$^{-1}$ N ha$^{-1}$ at Lare season 2, whereas the corresponding values at Maai Mahiu were only 54.65 kg $kg^{-1}$ N $ha^{-1}$ in season 1 and 177.63 kg $kg^{-1}$ N $ha^{-1}$ in season 2. Seasonal differences were also evident. In many treatments, season two produced higher PFP values than season one, particularly at Maai Mahiu. The treatment with 200 kg $ha^{-1}$ organic fertilizer with mulch increased from 94.09 kg $kg^{-1}$ N $ha^{-1}$ in season one to 340.04 kg $kg^{-1}$ N $ha^{-1}$ in season two at Maai Mahiu. Similarly, 400 kg $ha^{-1}$ organic fertilizer with mulch increased from 54.65 kg $kg^{-1}$ N $ha^{-1}$ in season 1 to 177.63 kg $kg^{-1}$ N $ha^{-1}$ in season 2. At Lare, seasonal differences were also observed, though they were generally smaller. At 200 kg $ha^{-1}$ organic fertilizer with mulch increased from 400.79 kg $kg^{-1}$ N $ha^{-1}$ in season one to 468.24 kg $kg^{-1}$ N $ha^{-1}$ in season two. The higher PFP values observed at Lare were because of favourable soil fertility and moisture conditions, allowing crops to utilize applied nutrients more efficiently. In contrast, the relatively lower PFP values at Maai Mahiu may reflect greater moisture limitations and poorer soil conditions, which restricted nutrient uptake and crop productivity.

### 3.3. Relative Yield (RY) (Kg $ha^{-1}$)

The results shown in Table 4 below indicate that Relative Yield (RY) was significantly affected by fertilizer treatment, mulch application, site, and season. Significant interaction effects among these factors indicated that crop response to integrated nutrient management differed across environments. The observed variations highlight the importance of site-specific and season-specific nutrient management strategies for maximizing yield performance. The treatments had a significant influence on Relative Yield (RY) across both Lare and Maai Mahiu sites and across the two seasons. Generally, RY increased with the integration of mineral fertilizer, organic fertilizer, and mulch, although the magnitude of response varied depending on the site and season. Across both sites, the highest RY values were observed in treatments that combined higher fertilizer inputs with mulch. Under the treatment with 150 kg $ha^{-1}$ NPK and 600 kg $ha^{-1}$ organic fertilizer with mulch recorded very high RY values of 2495.13 kg $ha^{-1}$ at Lare season 1, 304.33 kg $ha^{-1}$ at Maai Mahiu season 1, 2440.84 kg $ha^{-1}$ at Lare season 2, and 1984.89 kg $ha^{-1}$ at Maai Mahiu season 2. Similarly, the treatment with 150 kg $ha^{-1}$ NPK and 200 kg $ha^{-1}$ organic fertilizer with mulch produced high RY values of 2362.24 kg $ha^{-1}$ at Lare season 1, 276.00 kg $ha^{-1}$ at Maai Mahiu season 1, 2351.62 kg $ha^{-1}$ at Lare season 2, and 1711.46 kg $ha^{-1}$ at Maai Mahiu season 2. In the 75 kg $ha^{-1}$ NPK fertilizer treatments, RY values were also relatively high, particularly when organic fertilizer was included. At 75 kg $ha^{-1}$ NPK combined with 400 kg $ha^{-1}$ organic fertilizer without mulch produced 2089.90 kg $ha^{-1}$ at Lare season1, 260.00 kg $ha^{-1}$ at Maai Mahiu season 1, 2081.09 kg $ha^{-1}$ at Lare season 2, and 1163.82 kg $ha^{-1}$ at Maai Mahiu season 2. This indicates that moderate fertilizer inputs still produced substantial yield responses. However, treatments with no mineral fertilizer but only organic fertilizer generally produced lower RY values. At 200 kg $ha^{-1}$ organic fertilizer without mulch recorded 297.45 kg $ha^{-1}$ at Lare season 1, 155.67 kg $ha^{-1}$ at Maai Mahiu season 1, 316.66 kg $ha^{-1}$ at Lare season 2, and 398.73 kg $ha^{-1}$ at

Maai Mahiu season 2. Although the highest fertilizer combinations produced the greatest yield increases, moderate fertilizer (400 - 600 kg ha$^{-1}$ organic fertilizer) and 75 kg ha$^{-1}$ NPK combinations offer better economic efficiency for farmers, since they require lower input costs while still producing substantial yield gains.

**Table 4.** Mean values for relative yield for Dolichos crop as affected by integrated nutrient management and mulching application at Lare and Maai Mahiu Nakuru County Kenya during season 1 (September 2024-January 2025) and season 2 (April-August 2025).

| Treatments | | | | | | |
|---|---|---|---|---|---|---|
| NPK (Kg/Ha) | Organic Fertilizer (Kg/Ha) | Organic Mulch | Lare S1 | Maai Mahiu S1 | Lare S2 | Maai Mahiu S2 |
| 0 | 200 | $M_0$ | $297.45^{g}$ | $155.67^{hijk}$ | $316.66^{i}$ | $398.73^{h}$ |
| | 400 | $M_0$ | $440.72^{fg}$ | $153.33^{ijk}$ | $486.72^{h}$ | $382.99^{h}$ |
| | 600 | $M_0$ | $1558.11^{abcde}$ | $222.00^{defghi}$ | $1550.95^{ef}$ | $874.43^{efg}$ |
| | 200 | $M_1$ | $287.61^{g}$ | $139.67^{k}$ | $253.03^{i}$ | $376.34^{h}$ |
| | 400 | $M_1$ | $1430.21^{bcdef}$ | $145.33^{jk}$ | $1632.49^{e}$ | $437.22^{h}$ |
| | 600 | $M_1$ | $1772.80^{abcde}$ | $188.00^{ghijk}$ | $1802.71^{def}$ | $852.91^{efg}$ |
| 75 | 0 | $M_0$ | $1001.17^{defg}$ | $191.33^{fghijk}$ | $1035.04^{g}$ | $675.71^{gh}$ |
| | 200 | $M_0$ | $1338.48^{cdefg}$ | $200.00^{efghijk}$ | $1407.50^{f}$ | $712.31^{fgh}$ |
| | 400 | $M_0$ | $2089.90^{abc}$ | $260.00^{bcdef}$ | $2081.09^{cd}$ | $1163.82^{cde}$ |
| | 600 | $M_0$ | $2562.84^{a}$ | $193.33^{fghijk}$ | $2636.57^{a}$ | $670.56^{gh}$ |
| | 0 | $M_1$ | $1820.28^{abcde}$ | $240.67^{bcdefg}$ | $1777.85^{def}$ | $1375.85^{bcd}$ |
| | 200 | $M_1$ | $2061.70^{abcd}$ | $223.67^{cdefgh}$ | $1989.31^{cde}$ | $1195.24^{cde}$ |
| | 400 | $M_1$ | $2236.60^{abc}$ | $252.00^{bcdefg}$ | $2209.11^{c}$ | $1484.05^{bcd}$ |
| | 600 | $M_1$ | $905.81^{efg}$ | $212.00^{defghij}$ | $1435.77^{f}$ | $1091.28^{def}$ |
| 150 | 0 | $M_0$ | $1625.89^{abcde}$ | $242.00^{bcdefg}$ | $1652.20^{e}$ | $1027.01^{efg}$ |
| | 200 | $M_0$ | $1959.21^{abcd}$ | $283.50^{abc}$ | $1963.96^{cde}$ | $1510.12^{bc}$ |
| | 400 | $M_0$ | $1863.81^{abcde}$ | $308.33^{ab}$ | $1956.33^{cdef}$ | $1510.39^{bc}$ |
| | 600 | $M_0$ | $2144.08^{abc}$ | $332.33^{a}$ | $2242.95^{bc}$ | $1686.01^{ab}$ |
| | 0 | $M_1$ | $2167.87^{abc}$ | $197.33^{fghijk}$ | $2024.79^{cde}$ | $936.63^{efg}$ |
| | 200 | $M_1$ | $2362.24^{abc}$ | $276.00^{abcd}$ | $2351.62^{b}$ | $1711.46^{ab}$ |
| | 400 | $M_1$ | $1318.49^{cdefg}$ | $267.67^{abcde}$ | $1344.15^{fg}$ | $1639.02^{ab}$ |
| | 600 | $M_1$ | $2495.13^{ab}$ | $304.33^{ab}$ | $2440.84^{b}$ | $1984.89^{a}$ |
| HSD (0.05) | | | 9.36 | 5.29 | 6.94 | 5.30 |

Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ according to Tukey's HSD test. (S1—season 1, S1—season 2, $M_0$—without mulch, $M_1$—with mulch).

Mulching generally improved relative yield across both sites and seasons. At the treatment with 75 kg ha$^{-1}$ NPK and no organic fertilizer, without mulch produced 1001.17 kg ha$^{-1}$ at Lare season 1 and 1035.04 kg ha$^{-1}$ at Lare season 2, whereas the same treatment with mulch increased RY to 1820.28 kg ha$^{-1}$ at Lare season 1 and 1777.85 kg ha$^{-1}$ at Lare season 2. At Maai Mahiu, the same treatments increased from 191.33 kg ha$^{-1}$ and 675.71 kg ha$^{-1}$ without mulch to 240.67 kg ha$^{-1}$ and 1375.85 kg ha$^{-1}$ with mulch in seasons 1 and 2, respectively. Similarly, the treatment with 150 kg ha$^{-1}$ NPK and 200 kg ha$^{-1}$ organic fertilizer without mulch recorded 1959.21 kg ha$^{-1}$ at Lare season 1 and 1963.96 kg ha$^{-1}$ at Lare season 2, while the addition of mulch increased RY to 2362.24 kg ha$^{-1}$ at Lare season 1 and 2351.62 kg ha$^{-1}$ at Lare season 2. At Maai Mahiu, the same treatments increased from 283.50 kg ha$^{-1}$ in season 1 and 1510.12 kg ha$^{-1}$ in season 2 without mulch to 276.00 kg ha$^{-1}$ in season 1 and 1711.46 kg ha$^{-1}$ in season 2 with mulch. Mulch improved yield performance in semi-arid environments such as Maai Mahi.

Across most treatments, Lare consistently recorded higher RY values than Maai Mahiu. The treatment with 75 kg ha$^{-1}$ NPK and 400 kg ha$^{-1}$ organic fertilizer without mulch produced 2089.90 kg ha$^{-1}$ at Lare season 1 compared with only 260.00 kg ha$^{-1}$ at Maai Mahiu season 1, and 2081.09 kg ha$^{-1}$ at Lare season 2 compared with 1163.82 kg ha$^{-1}$ at Maai Mahiu season 2. Similarly, the treatment with 150 kg ha$^{-1}$ NPK and 600 kg ha$^{-1}$ organic fertilizer without mulch recorded 2144.08 kg ha$^{-1}$ at Lare season 1 and 2242.95 kg ha$^{-1}$ at Lare season 2, whereas the corresponding values at Maai Mahiu were 332.33 kg ha$^{-1}$ in season 1 and 1686.01 kg ha$^{-1}$season 2. Seasonal variation was also evident. Season two produced higher RY values than season one, particularly at Maai Mahiu. Under the treatment with 75 kg ha$^{-1}$ NPK and no organic fertilizer without mulch increased from 191.33 kg ha$^{-1}$ in season 1 to 675.71 kg ha$^{-1}$ in season 2. Similarly, 150 kg ha$^{-1}$ NPK and 600 kg ha$^{-1}$ organic fertilizer with mulch increased from 304.33 kg ha$^{-1}$ in season 1 to 1984.89 kg ha$^{-1}$ in season 2. Lare had more favourable soil fertility and moisture conditions, which allowed crops to respond better to fertilizer inputs. In contrast, the lower yield responses observed at Maai Mahiu reflected greater moisture stress and less favourable soil conditions.

### 3.4. Yield Response (YR) (%)

Yield Response (YR) was significantly influenced by fertilizer treatment, mulch application, site, and season, with significant interaction effects observed among the factors. The magnitude of yield response varied across fertilizer combinations and environmental conditions, indicating that the effectiveness of nutrient inputs depended on both management practices and site-specific growing conditions. Across the treatments without mineral fertilizer, yield response increased with increasing organic fertilizer rates as shown in **Table 5** below. Under the application of 600 kg ha$^{-1}$ organic fertilizer without mulch, relatively high YR values of 248.67% were obtained at Lare season 1 and 297.01% at Maai Mahiu season 1, while in season 2 the same treatment recorded 171.33% at Lare season 2 and 221.84% at Maai Mahiu season 2. In contrast, lower organic fertilizer levels such as 200 kg ha$^{-1}$ produced smaller responses, with 127.67% at Lare season 1, 172.72% at Maai Mahiu season 1, 61.82% at Lare season 2, and 155.63% at Maai Mahiu season 2. The introduction of 75 kg NPK ha$^{-1}$ improved yield response across both sites. The treatment combining 75 kg ha$^{-1}$ NPK with 600 kg ha$^{-1}$ organic fertilizer without mulch produced the highest responses at Lare, reaching 343.00% in season 1 and 267.72% in season 2, while at Maai Mahiu the same treatment recorded 268.21% in season 1 and 193.49% in season 2. Similarly, 75 kg ha$^{-1}$ NPK combined with 400 kg ha$^{-1}$ organic fertilizer without mulch produced high responses of 297.00% at Lare season 1 and 216.51% at Lare season 2, and 391.12% at Maai Mahiu season 1 and 260.16% at Maai Mahiu season 2. The highest yield responses were observed in treatments with 150 kg NPK ha$^{-1}$ combined with organic fertilizer. At 150 kg ha$^{-1}$ NPK and 600 kg ha$^{-1}$ organic fertilizer without mulch produced 302.00% at Lare season 1 and 231.58% at Lare season 2, while at Maai Mahiu the same treatment recorded 437.11% in season 1 and 332.01% in season 2. Similarly, 150 kg ha$^{-1}$ NPK and 200 kg ha$^{-1}$ organic fertilizer without mulch recorded 261.00% at Lare season 1 and 178.44% at Lare season 2, and 461.53% and 283.43% at Maai Mahiu season 1 and season 2, respectively. Moderate fertilizer combinations as 75 kg ha$^{-1}$ NPK with 400 kg ha$^{-1}$ organic fertilizer produced responses of 297.00% at Lare season 1 and 391.12% at Maai Mahiu season 1, provided a better balance between yield gain and input cost for resource-constrained farmers.

Mulching enhanced yield response across both sites, particularly in treatments involving mineral fertilizer. The treatment with 75 kg ha$^{-1}$ NPK without organic fertilizer increased from 194.00% at Lare season 1 and 125.13% at Lare season 2 without mulch to 224.67% and 134.05% with mulch in seasons 1 and 2, respectively. At Maai Mahiu, the same treatment increased substantially from 188.77% and 191.36% without mulch to 466.29% and 240.50% with mulch in seasons 1 and 2, respectively. Similarly, 75 kg ha$^{-1}$ NPK combined with 400 kg ha$^{-1}$ organic fertilizer increased from 297.00% at Lare season 1 and 216.51% at Lare season 2 without mulch to 253.67% and 159.73% with mulch, while at Maai Mahiu the same treatments increased from 391.12% and 260.16% without mulch to 444.92% and 251.98% with mulch. Mulching also enhanced yield response in some high nitrogen treatments. At 150 kg ha$^{-1}$ NPK with 600 kg ha$^{-1}$ organic fertilizer increased from 437.11% at Maai Mahiu season 1 without mulch to 538.97% with mulch, representing the highest yield response observed across the treatments. At Lare, the same treatment increased from 302.00% without mulch to 270.67% with mulch, while season 2 recorded 231.58% without mulch and 244.08% with mulch. Mulching increased the return on fertilizer investment by enhancing yield response without requiring additional fertilizer inputs, making it a cost-effective practice for improving productivity.

In many treatments, Maai Mahiu recorded higher yield response percentages than Lare, particularly in season 1. The treatment with 150 kg ha$^{-1}$ NPK and 200 kg ha$^{-1}$ organic fertilizer without mulch recorded 261.00% at Lare season 1 compared with 461.53% at Maai Mahiu season 1. Similarly, 75 kg ha$^{-1}$ NPK without organic fertilizer with mulch produced 224.67% at Lare season 1 but 466.29% at Maai Mahiu season 1. However, in season 2, Lare often recorded higher responses in several treatments. The treatment with 75 kg ha$^{-1}$ NPK and 600 kg ha$^{-1}$ organic fertilizer without mulch produced 267.72% at Lare season 2 compared with 193.49% at Maai Mahiu season 2. Similarly, 150 kg ha$^{-1}$ NPK and 600 kg ha$^{-1}$ organic fertilizer without mulch recorded 231.58% at Lare season 2 compared with 332.01% at Maai Mahiu season 2, although the latter still remained relatively high.

**Table 5.** Mean values for yield response for Dolichos crop as affected by integrated nutrient management and mulching application at Lare and Maai Mahiu Nakuru County Kenya during season 1 (September 2024-January 2025) and season 2 (April-August 2025).

| Treatments | | | | | | |
|---|---|---|---|---|---|---|
| NPK (Kg/Ha) | Organic Fertilizer (Kg/Ha) | Organic Mulch | Lare S1 | Maai Mahiu S1 | Lare S2 | Maai Mahiu S2 |
| 0 | 200 | $M_0$ | 127.67$^{fg}$ | 172.72$^{h}$ | 61.82$^{ef}$ | 155.63$^{hijk}$ |
| | 400 | $M_0$ | 141.33$^{efg}$ | 145.72$^{h}$ | 75.95$^{ef}$ | 153.17$^{ijk}$ |
| | 600 | $M_0$ | 248.67$^{abcd}$ | 297.01$^{ef}$ | 171.33$^{bc}$ | 221.84$^{defghi}$ |
| | 200 | $M_1$ | 110.83$^{g}$ | 139.04$^{h}$ | 47.73$^{efg}$ | 139.78$^{k}$ |
| | 400 | $M_1$ | 198.00$^{cdefg}$ | 157.33$^{h}$ | 127.01$^{cde}$ | 145.30$^{jk}$ |
| | 600 | $M_1$ | 220.33$^{bcdef}$ | 330.55$^{de}$ | 134.31$^{cde}$ | 187.89$^{ghijk}$ |
| 75 | 0 | $M_0$ | 194.00$^{cdefg}$ | 188.77$^{h}$ | 125.13$^{cde}$ | 191.36$^{fghijk}$ |
| | 200 | $M_0$ | 227.00$^{bcde}$ | 314.55$^{de}$ | 158.08$^{bcd}$ | 199.89$^{efghijk}$ |
| | 400 | $M_0$ | 297.00$^{ab}$ | 391.12$^{c}$ | 216.51$^{ab}$ | 260.16$^{bcdef}$ |
| | 600 | $M_0$ | 343.00$^{a}$ | 268.21$^{fg}$ | 267.72$^{a}$ | 193.49$^{fghijk}$ |
| | 0 | $M_1$ | 224.67$^{bcdef}$ | 466.29$^{b}$ | 134.05$^{cde}$ | 240.50$^{bcdefg}$ |
| | 200 | $M_1$ | 241.33$^{bcd}$ | 388.14$^{c}$ | 146.36$^{cde}$ | 223.72$^{cdefgh}$ |
| | 400 | $M_1$ | 253.67$^{abcd}$ | 444.92$^{b}$ | 159.73$^{bcd}$ | 251.98$^{bcdefg}$ |
| | 600 | $M_1$ | 163.33$^{defg}$ | 391.36$^{c}$ | 117.13$^{cdef}$ | 212.06$^{defghij}$ |
| 150 | 0 | $M_0$ | 253.33$^{abcd}$ | 345.00$^{cd}$ | 179.21$^{abc}$ | 242.14$^{bcdefg}$ |
| | 200 | $M_0$ | 261.00$^{abc}$ | 461.53$^{b}$ | 178.44$^{abc}$ | 283.43$^{abc}$ |
| | 400 | $M_0$ | 276.47$^{abc}$ | 417.03$^{bc}$ | 206.19$^{ab}$ | 308.31$^{ab}$ |
| | 600 | $M_0$ | 302.00$^{ab}$ | 437.11$^{b}$ | 231.58$^{a}$ | 332.01$^{a}$ |
| | 0 | $M_1$ | 248.67$^{abcd}$ | 317.02$^{de}$ | 224.79$^{cde}$ | 197.17$^{fghijk}$ |
| | 200 | $M_1$ | 262.00$^{abc}$ | 470.30$^{b}$ | 251.62$^{b}$ | 275.88$^{abcd}$ |
| | 400 | $M_1$ | 190.67$^{cdefg}$ | 444.18$^{b}$ | 1344.15$^{fg}$ | 267.56$^{abcde}$ |
| | 600 | $M_1$ | 270.67$^{abc}$ | 538.97$^{a}$ | 240.84$^{b}$ | 304.35$^{ab}$ |
| HSD (0.05) | | | 8.90 | 5.36 | 3.05 | 9.75 |

Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ according to Tukey's HSD test. (S1—season 1, S1—season 2, $M_0$—without mulch, $M_1$—with mulch).

### 3.5. Crop Total Grain Yield (Kg $ha^{-1}$)

In Table 6 below, total yield responded to increasing fertilizer inputs. Under the control treatment (0 kg $ha^{-1}$ NPK, 0 kg $ha^{-1}$ organic fertilizer, $M_0$), the lowest yields were recorded across all environments, with 1055.76 kg $ha^{-1}$ at Lare season 1, 735.34 kg $ha^{-1}$ at Maai Mahiu season 1, 1128.25 kg $ha^{-1}$ at Lare season 2, and 838.01 kg $ha^{-1}$ at Maai Mahiu season 2, indicating nutrient limitation. Increasing organic fertilizer under the same NPK level slightly improved yields. Under 0 kg $ha^{-1}$ NPK and 600 kg $ha^{-1}$ organic fertilizer without mulch, yield increased to 2613.87 kg $ha^{-1}$ at Lare season 1, 1609.77 kg $ha^{-1}$ at Maai Mahiu season 1, 2679.19 kg $ha^{-1}$ at Lare season 2, and 1702.17 kg $ha^{-1}$ at Maai Mahiu season 2, suggesting that organic inputs contributed to improved soil fertility and crop performance. When 75 kg NPK $ha^{-1}$ was applied without mulch, yields increased progressively with organic fertilizer rates, reaching 3618.60 kg $ha^{-1}$ at Lare season 1, 1405.90 kg $ha^{-1}$ at Maai Mahiu season 1, 3764.82 kg $ha^{-1}$ at Lare season 2, and 1477.92 kg $ha^{-1}$ at Maai Mahiu season 2 under 600 kg organic fertilizer. Similarly, under 150 kg NPK $ha^{-1}$ without mulch, yields ranged from 2681.66 kg $ha^{-1}$ at Lare season 1 to 3199.84 kg $ha^{-1}$, while at Maai Mahiu season 1 they ranged from 1762.36 kg $ha^{-1}$ to 2421.36 kg $ha^{-1}$ as organic fertilizer increased. The highest yields were observed under 150 kg NPK combined with higher organic fertilizer rates and mulch. For Under 150 kg $ha^{-1}$ NPK and 600 kg $ha^{-1}$ organic fertilizer with mulch, yields reached 3962.67 kg $ha^{-1}$ at Lare season 1, 2968.68 kg $ha^{-1}$ at Maai Mahiu season 1, 4212.65 kg $ha^{-1}$ at Lare season 2, and 3249.39 kg $ha^{-1}$ at Maai Mahiu season 2, Integrated nutrient management significantly enhanced productivity due to improved nutrient availability, better soil structure, and enhanced plant growth.

Mulch application increased total yield across most fertilizer combinations. Under 0 kg $ha^{-1}$ NPK and 0 kg $ha^{-1}$ organic fertilizer, yield increased from 1055.76 kg $ha^{-1}$ to 1467.54 kg $ha^{-1}$ at Lare season 1, 735.34 kg $ha^{-1}$ to 983.79 kg $ha^{-1}$ at Maai Mahiu season 1, 1128.25 kg $ha^{-1}$ to 1771.80 kg $ha^{-1}$ at Lare season 2, and 838.01 kg $ha^{-1}$ to 1237.31 kg $ha^{-1}$ at Maai Mahiu season 2 when mulch was applied. Similarly, under 0 kg $ha^{-1}$ NPK and 600 kg $ha^{-1}$ organic fertilizer, yields increased from 2613.87 kg $ha^{-1}$ to 3240.34 kg $ha^{-1}$ at Lare season 1, 1609.77 kg $ha^{-1}$ to 1836.71 kg $ha^{-1}$ at Maai Mahiu season 1, 2679.19 kg $ha^{-1}$ to 3574.51 kg $ha^{-1}$ at Lare season 2, and 1702.17 kg $ha^{-1}$ to 2091.45 kg $ha^{-1}$ at Maai Mahiu season 2 following mulch application. A similar pattern was observed under 75 kg $ha^{-1}$ NPK, where yields increased markedly with mulch. Under 75 kg $ha^{-1}$ NPK and 400 kg $ha^{-1}$ organic fertilizer, yield increased from 3145.66 kg $ha^{-1}$ to 3704.14 kg $ha^{-1}$ at Lare season 1, 1899.16 kg $ha^{-1}$ to 2467.84 kg $ha^{-1}$ at Maai Mahiu season 1, 3209.35 kg $ha^{-1}$ to 3980.91 kg $ha^{-1}$ at Lare season 2, and 2010.33 kg $ha^{-1}$ to 2753.95 kg $ha^{-1}$ at Maai Mahiu season 2 when mulch was applied. Similarly, under 150 kg $ha^{-1}$ NPK and 200 kg $ha^{-1}$ organic fertilizer, yield increased from 3153.90 kg $ha^{-1}$ to 3829.77 kg $ha^{-1}$ at Lare season 1, 2379.73 kg $ha^{-1}$ to 2695.25 kg $ha^{-1}$ at Maai Mahiu season 1, 3278.30 kg $ha^{-1}$ to 4123.43 kg $ha^{-1}$ at Lare season 2, and 2484.51 kg $ha^{-1}$ to 2896.87 kg $ha^{-1}$ at Maai Mahiu season 2. Mulch enhanced crop productivity improving soil moisture conservation, reducing evaporation losses, and enhancing nutrient use efficiency.

**Table 6.** Mean values for Dolichos crop total grain yield as affected by integrated nutrient management and mulching application at Lare and Maai Mahiu Nakuru County Kenya during season 1 (September 2024-January 2025) and season 2 (April-August 2025).

| Treatments | | | | | | |
|---|---|---|---|---|---|---|
| NPK (Kg/Ha) | Organic Fertilizer (Kg/Ha) | Organic Mulch | Lare S1 | Maai Mahiu S1 | Lare S2 | Maai Mahiu S2 |
| 0 | 0 | $M_0$ | 1055.76$^{i}$ | 735.34$^{l}$ | 1128.25$^{l}$ | 838.01$^{k}$ |
| | 200 | $M_0$ | 1353.210$^{hi}$ | 1134.07$^{jkl}$ | 1444.91$^{k}$ | 1233.58$^{jk}$ |
| | 400 | $M_0$ | 1496.48$^{hi}$ | 1118.33$^{jkl}$ | 1614.97$^{j}$ | 1225.31$^{jk}$ |
| | 600 | $M_0$ | 2613.87$^{defg}$ | 1609.77$^{ghi}$ | 2679.19$^{fg}$ | 1702.17$^{ghij}$ |
| | 0 | $M_1$ | 1467.54$^{hi}$ | 983.79$^{kl}$ | 1771.80$^{i}$ | 1237.31$^{jk}$ |
| | 200 | $M_1$ | 1603.15$^{ghi}$ | 1360.14$^{ijk}$ | 1872.94$^{h}$ | 1541.99$^{hij}$ |
| | 400 | $M_1$ | 2897.75$^{bcdef}$ | 1421.01$^{hij}$ | 3404.29$^{cd}$ | 1713.76$^{ghij}$ |
| | 600 | $M_1$ | 3240.34$^{abcde}$ | 1836.71$^{efgh}$ | 3574.51$^{c}$ | 2091.45$^{defg}$ |
| 75 | 0 | $M_0$ | 2056.93$^{fghi}$ | 1411.05$^{hijk}$ | 2163.29$^{g}$ | 1509.50$^{hij}$ |
| | 200 | $M_0$ | 2394.25$^{efgh}$ | 1447.65$^{hij}$ | 2535.75$^{fg}$ | 1520.00$^{hij}$ |
| | 400 | $M_0$ | 3145.66$^{abcde}$ | 1899.16$^{efg}$ | 3209.35$^{de}$ | 2010.33$^{efgh}$ |
| | 600 | $M_0$ | 3618.60$^{abcd}$ | 1405.90$^{ijk}$ | 3764.82$^{bc}$ | 1477.92$^{ij}$ |
| | 0 | $M_1$ | 3287.81$^{abcde}$ | 2359.64$^{bcd}$ | 3549.66$^{c}$ | 2643.14$^{bc}$ |
| | 200 | $M_1$ | 3529.24$^{abcd}$ | 2179.03$^{def}$ | 3761.11$^{bc}$ | 2564.97$^{bcd}$ |
| | 400 | $M_1$ | 3704.14$^{abc}$ | 2467.84$^{bcd}$ | 3980.91$^{abc}$ | 2753.95$^{abc}$ |
| | 600 | $M_1$ | 2373.34$^{efgh}$ | 2075.08$^{def}$ | 2705.91$^{f}$ | 2345.50$^{cde}$ |
| 150 | 0 | $M_0$ | 2681.66$^{cdef}$ | 1762.36$^{fghi}$ | 2780.44$^{f}$ | 1783.21$^{fghi}$ |
| | 200 | $M_0$ | 3153.90$^{abcde}$ | 2379.73$^{bcd}$ | 3278.30$^{de}$ | 2484.51$^{bcde}$ |
| | 400 | $M_0$ | 2919.57$^{abcdef}$ | 2245.73$^{cde}$ | 3084.57$^{ef}$ | 2319.37$^{cde}$ |
| | 600 | $M_0$ | 3199.84$^{abcde}$ | 2421.36$^{bcd}$ | 3371.20$^{d}$ | 2547.09$^{bcd}$ |
| | 0 | $M_1$ | 3635.40$^{abcd}$ | 1920.43$^{efg}$ | 3796.60$^{bc}$ | 2236.00$^{cdef}$ |
| | 200 | $M_1$ | 3829.77$^{ab}$ | 2695.25$^{ab}$ | 4123.43$^{ab}$ | 2896.87$^{ab}$ |
| | 400 | $M_1$ | 2786.03$^{bcdef}$ | 2622.82$^{abc}$ | 3115.95$^{e}$ | 2881.82$^{ab}$ |
| | 600 | $M_1$ | 3962.67$^{a}$ | 2968.68$^{a}$ | 4212.65$^{a}$ | 3249.39$^{a}$ |
| HSD (0.05) | | | 10.46 | 10.02 | 10.76 | 10.56 |

Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ according to Tukey's HSD test. (S1—season 1, S1—season 2, $M_0$—without mulch, $M_1$—with mulch).

Seasonal and site differences were evident in total yield. In most treatments, Season 2 produced higher yields than season 1 at both sites. Under control, 0 kg ha$^{-1}$ NPK, 0 kg ha$^{-1}$ organic fertilizer, and no mulch, yield increased from 1055.76 kg ha$^{-1}$ to 1128.25 kg ha$^{-1}$ at Lare from season 1 to season 2 and from 735.34 kg ha$^{-1}$ to 838.01 kg ha$^{-1}$ at Maai Mahiu from season 1 to season 2. Similarly, under 150 kg ha$^{-1}$ NPK and 600 kg ha$^{-1}$ organic fertilizer with mulch, yield increased from 3962.67 kg ha$^{-1}$ to 4212.65 kg ha$^{-1}$ at Lare season 1 to season 2 and from 2968.68 to 3249.39 kg ha$^{-1}$ at Maai Mahiu season 1 to season 2, indicating more favourable growing conditions during the second season. Site differences were evident across most treatments. In many cases, Lare recorded higher yields than Maai Mahiu. Under 75 kg ha$^{-1}$ NPK and 400 kg ha$^{-1}$ organic fertilizer with mulch, yields were 3704.14 kg ha$^{-1}$ at Lare season 1 and 3980.91 kg ha$^{-1}$ at Lare season 2, compared with 2467.84 kg ha$^{-1}$ at Maai Mahiu season 1 and 2753.95 kg ha$^{-1}$ at Maai Mahiu season 2. Similarly, under 150 kg ha$^{-1}$ NPK and 600 kg ha$^{-1}$ organic fertilizer with mulch, yields were 3962.67 kg ha$^{-1}$ and 4212.65 kg ha$^{-1}$ at Lare season 1 and season 2, respectively, compared with 2968.68 kg ha$^{-1}$ and 3249.39 kg ha$^{-1}$ at Maai Mahiu season 1 and season 2, respectively. Overall, Lare and Season 2 generally produced higher yields. Environmental conditions such as rainfall distribution, soil fertility, and climatic factors favoured better crop growth and productivity at that site and season.

## 4. Discussion

From the above results, the present study demonstrated that integrated nutrient management combined with mulching improved agronomic performance, fertilizer use efficiency, and grain yield of Dolichos bean across both sites and seasons in the semi-arid areas of Nakuru County, Kenya. Treatments that combined moderate rates of NPK fertilizer (≤75 kg ha$^{-1}$) with organic fertilizer (400 - 600 kg ha$^{-1}$) consistently outperformed sole fertilizer applications and the unfertilized controls. The superior performance of these integrated treatments is attributed to improved nutrient synchronization, whereby readily available nutrients from NPK fertilizer supported early crop growth while nutrients released gradually from organic fertilizer sustained crop demand during reproductive development. This complementary nutrient supply enhanced pod formation, grain filling, and final grain yield while minimizing periods of nutrient deficiency. In addition, organic amendments improved soil organic matter content, microbial activity, and nutrient retention, thereby increasing nutrient availability and uptake efficiency throughout the growing season. Similar findings have been reported in integrated soil fertility studies where combining organic and inorganic nutrient sources improved nutrient use efficiency, crop growth, and productivity under tropical and semi-arid conditions [12] [13]. The low performance observed under the control treatment further confirms that poor soil fertility and inadequate nutrient availability remain major constraints to legume productivity in semi-arid agroecosystems.

Mulching enhanced crop performance and fertilizer use efficiency across both sites and seasons. Higher grain yield, seed weight, AUE, PFP, RY, and YR under mulched treatments indicate that the benefits of fertilizer application were strongly influenced by soil moisture availability. In semi-arid environments, nutrient uptake is often constrained not only by nutrient supply but also by insufficient soil moisture to facilitate nutrient dissolution, root growth, and nutrient transport to plant roots. Mulch improved the efficiency of applied fertilizers by conserving soil moisture, moderating soil temperature fluctuations, and creating favourable conditions for microbial activity and nutrient mineralization. These effects enhanced root development and nutrient uptake, allowing crops to utilize a greater proportion of the applied nutrients. Similar findings have been reported by [14] [15], who emphasized that mulching significantly improves soil water conservation, nutrient cycling, and crop resilience under moisture-limited conditions. The decline in agronomic use efficiency and other fertilizer use efficiency indices at higher fertilizer application rates, particularly under 150 kg $ha^{-1}$ NPK combined with high organic fertilizer inputs, suggests that nutrient supply exceeded the crop's capacity to effectively utilize the additional nutrients. Although these treatments often produced relatively high grain yields, the yield increase was not proportional to the quantity of nutrients applied, resulting in lower efficiency values. This pattern reflects the principle of diminishing returns, whereby each additional unit of fertilizer contributes progressively smaller yield gains once crop nutrient requirements approach saturation. Excess nutrient availability increased nutrient losses through leaching, fixation, volatilization, and temporary nutrient imbalances, thereby reducing nutrient recovery by the crop. Similar findings have been reported by [1] and [16] who indicated that nutrient use efficiency declines when fertilizer application exceeds crop demand.

The contrasting responses observed between Lare and Maai Mahiu further highlight the influence of local environmental conditions on nutrient use efficiency. Lare generally produced higher yields and fertilizer use efficiency values, suggesting that soil fertility and moisture conditions were more favorable for nutrient uptake and crop growth. Under such conditions, a larger proportion of applied nutrients converted into grain yield. In contrast, Maai Mahiu showed a stronger response to mulching, indicating that moisture limitation rather than nutrient supply was a major constraint to crop productivity. The greater effectiveness of mulch at Maai Mahiu suggests that conserving soil water improved the crop's ability to access and utilize applied nutrients. These findings demonstrate that the effectiveness of nutrient management practices depends on the interaction between nutrient availability and site-specific environmental factors, particularly soil moisture status.

Seasonal variation also influenced crop performance and fertilizer use efficiency. The generally superior performance observed during season 2 was attributed to more favorable rainfall distribution and the residual effects of organic fertilizer applied in the previous season. Organic amendments continue to decompose after application, gradually releasing nutrients and improving soil structure, water-holding capacity, and microbial activity. Consequently, the cumulative benefits of organic inputs enhanced nutrient availability and nutrient uptake efficiency in the second season. Overall, the findings indicate that the productivity benefits of integrated nutrient management are not solely due to increased nutrient supply but also arise from improved nutrient synchronization, enhanced soil conditions, and greater resilience to moisture stress. These results support the use of integrated nutrient management combined with mulching as a sustainable strategy for improving Dolichos productivity and fertilizer use efficiency in semi-arid environments. Similar findings by [17] and [18] showed that integrated nutrient management significantly improves soil fertility status, nutrient availability, and crop response in degraded soils of sub-Saharan Africa.

## 5. Correlation Matrices

Correlation analysis is a statistical tool used to quantify the strength and direction of relationships between variables in agricultural research. In studies involving crop performance and nutrient management, it helps to describe how grain yield is associated with fertilizer use efficiency indices such as agronomic efficiency (AUE), partial factor productivity (PFP), relative yield (RY), and yield response (YR). However, it is important to note that RY and YR were derived directly from grain yield; therefore, they were not independent predictors of yield. As a result, correlations involving RY and YR were interpreted as descriptive numerical associations rather than evidence that they causally influence yield. Overall, the correlation analysis in this study was used to characterize patterns of association among variables and to support interpretation of nutrient use efficiency outcomes, rather than to infer causal drivers of yield performance.

### 5.1. Pearson Correlation Coefficient at Lare

In **Table 7** results below, the correlation matrix reveals strong relationships between grain yield and most fertilizer efficiency metrics, highlighting the integrated nature of productivity responses in Lare. Grain yield exhibited a very strong positive correlation with yield response ($r = 0.98$) and relative yield ($r = 0.91$), indicating that relative and yield-based efficiency indices were the most influential determinants of final productivity. This suggests that treatments that improved yield response relative to controls and maximum potential conditions directly translated into higher grain yield. A moderate positive relationship with agronomic use efficiency ($r = 0.67$) further indicates that agronomic efficiency contributed substantially to yield improvement. In contrast, the weak correlation between grain yield and partial factor productivity ($r = 0.20$) suggested that partial factor productivity was less sensitive in capturing yield variations under the experimental conditions; it does not account for incremental yield gains per unit nutrient applied.

Among the fertilizer efficiency metrics, agronomic use efficiency and partial factor productivity were strongly correlated ($r = 0.72$), implying that both indices responded similarly to nutrient application rates and management practices. However, partial factor productivity showed very weak relationships with relative yield (r = 0.07) and yield response (r = 0.15). The strong correlation between relative yield and yield response (r = 0.92) confirmed consistency between these two indices in describing yield performance relative to nutrient inputs and control treatments. Yield response and relative yield are the most reliable indicators of grain yield performance, while agronomic use efficiency provides supportive insight into nutrient use efficiency.

**Table 7.** Pearson correlation coefficient matrix for yield and fertilizer use efficiency metrics under integrated nutrient management and mulching application at Lare, Nakuru County, Kenya during season 1 (September 2024-January 2025) and season 2 (April-August 2025).

| Variables | Grain yield | AUE | PFP | RY | YR |
|---|---|---|---|---|---|
| Grain yield | 1 | 0.67 | 0.2 | 0.91 | 0.98 |
| AUE | 0.67 | 1 | 0.72 | 0.57 | 0.65 |
| PFP | 0.2 | 0.72 | 1 | 0.07 | 0.15 |
| RY | 0.91 | 0.57 | 0.07 | 1 | 0.92 |
| YR | 0.98 | 0.65 | 0.15 | 0.92 | 1 |

AUE = agronomic use efficiency, PFP = partial factor productivity, RY = relative yield, YR = yield response.

### 5.2. Pierson Correlation Coefficient Matrix across Seasons in Maai Mahiu

The results shown in Table 8 below show that in Maai Mahiu, the correlation matrix showed a different pattern compared to typical positive nutrient-yield relationships, indicating complex nutrient dynamics under semi-arid conditions. Grain yield exhibited a strong positive correlation with yield response (r = 0.74) and a moderate positive relationship with relative yield (r = 0.61), confirming that yield response-based indices remained the most reliable predictors of productivity. In contrast, grain yield showed weak negative correlations with agronomic use efficiency (r = −0.20) and partial factor productivity (r = −0.19). This inverse relationship implies that higher agronomic efficiency and partial factor productivity did not necessarily translate into increased yield.

Among the efficiency metrics, agronomic use efficiency and partial factor productivity maintained a strong positive correlation (r = 0.75), indicating consistency in how these two indices responded to nutrient application. However, both metrics showed negative relationships with relative yield (r = −0.32 for both) and weak to negative associations with yield response (r = −0.07 and −0.21, respectively). This further reinforces the disconnect between efficiency measures and yield response under the Maai Mahiu environment.

The strong positive correlation between relative yield and yield response (r = 0.65) indicated alignment between these response indices in explaining yield variation. In Maai Mahiu, yield performance was more strongly driven by response efficiency (relative yield and yield response) rather than input-use efficiency (agronomic use efficiency and partial factor productivity).

**Table 8.** Pearson correlation coefficient matrix for yield and fertilizer use efficiency metrics under integrated nutrient management and mulching application at Maai Mahiu, Nakuru County, Kenya during season 1 (September 2024-January 2025) and season 2 (April-August 2025).

| Variables | Grain yield | AUE | PFP | RY | YR |
|---|---|---|---|---|---|
| Grain yield | 1 | −0.2 | −0.19 | 0.61 | 0.74 |
| AUE | −0.2 | 1 | 0.75 | −0.32 | −0.07 |
| PFP | −0.19 | 0.75 | 1 | −0.32 | −0.21 |
| RY | 0.61 | −0.32 | −0.32 | 1 | 0.65 |
| YR | 0.74 | −0.07 | −0.21 | 0.65 | 1 |

AUE = agronomic use efficiency, PFP = partial factor productivity, RY = relative yield, YR = yield response.

## 6. Conclusion and Recommendation

### 6.1. Conclusions

Integrated nutrient management combining mineral fertilizer, organic fertilizer, and mulch significantly improved Dolichos bean yield performance and fertilizer use efficiency across sites and seasons. Moderate NPK fertilizer rates (≤75 kg NPK $ha^{-1}$) integrated with organic inputs and mulch produced the most balanced agronomic performance, achieving high yield responses of up to 391.12% and maintaining superior partial factor productivity of up to 468.24 kg grain $kg^{-1}$ N applied, indicating efficient nutrient utilization.

Although higher fertilizer rates increased absolute yield, they resulted in lower nutrient use efficiency, suggesting diminishing returns at excessive mineral fertilizer levels. Mulching further enhanced fertilizer efficiency and yield response, particularly under moisture-limited conditions, highlighting its importance in improving soil moisture conservation and nutrient availability.

Site-specific differences were evident, with Lare exhibiting greater nutrient productivity while Maai Mahiu showed stronger relative yield responses, reflecting contrasting environmental and soil fertility conditions. Overall, the findings indicated that moderate mineral NPK fertilizer rates (≤75 kg NPK $ha^{-1}$) integrated with organic inputs and mulching provide the most efficient, productive, and economically viable nutrient management strategy for Dolichos bean production in semi-arid agro-ecosystems.

### 6.2. Recommendations

Based on the findings of this study, the following recommendations are proposed for optimizing Dolichos bean production in semi-arid environments:

i. Promote integrated nutrient management (INM): Farmers should adopt combinations of mineral fertilizer, organic fertilizer, and mulch, as these treatments consistently improved yield and nutrient use efficiency.

ii. Use moderate fertilizer rates for economic efficiency: Moderate nitrogen application (75 kg NPK $ha^{-1}$) combined with organic fertilizer and mulch provided substantial yield gains while maintaining high nutrient productivity. In contrast, higher nitrogen rates (150 kg NPK $ha^{-1}$) sometimes increased yields, but were less efficient per unit fertilizer applied, making moderate rates more cost-effective for smallholder farmers.

iii. Incorporate mulching as a standard practice: Mulching significantly enhanced yield response and fertilizer efficiency by conserving soil moisture and improving nutrient availability. Applying mulch increased yield response; therefore, mulch should be integrated into Dolichos bean management, especially in moisture-limited conditions.

iv. Adopt site- and season-specific fertilizer strategies: Fertilizer and mulch management should be tailored to local conditions, as Lare generally showed higher nutrient productivity while Maai Mahiu exhibited stronger yield responses. This suggests that site-specific recommendations optimize both agronomic efficiency and economic returns.

v. Conduct long-term research for sustainability: Further trials are recommended to evaluate the long-term effects of integrated nutrient management on soil fertility, nutrient cycling, residual benefits, and cost-benefit ratios. This will ensure sustainable intensification and economic viability of Dolichos bean production systems.

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## Conflicts of Interest

The authors declare no conflict of interest. Materials used in the study were provided by REFOOTURE II Project—Egerton University (Kenya), which had no role in the design, analysis, interpretation, or publication of the study.

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## Appendix: Mean Values

Mean square values for agronomic use efficiency under integrated nutrient management and mulching treatments at Lare and Maai Mahiu, Nakuru County, Kenya during Season 1 (September 2024-January 2025) and Season 2 (April-August 2025).

| | | Season 1 | | Season 2 | |
|---|---|---|---|---|---|
| Source of variation | Df | Ms | F-value | Ms | F-value |
| Replication | 2 | 11,120 | $0.254^{ns}$ | 11,898 | 0.67*** |
| Treatment | 21 | 15,369 | 32.61*** | 16,232 | 0.92*** |
| Error | 43 | 4717 | | 17,686 | |

Codes: ns = not significant, "***" 0.001, "**" 0.01, "*" 0.05, "." 0.1.

Mean square values for partial factor productivity under integrated nutrient management and mulching treatments at Lare and Maai Mahiu, Nakuru County, Kenya during Season 1 (September 2024-January 2025) and Season 2 (April-August 2025).

| | | Season 1 | | Season 2 | |
|---|---|---|---|---|---|
| Source of variation | Df | Ms | F-value | Ms | F-value |
| Replication | 2 | 990.3 | 4.20* | 9075 | 0.49*** |
| Treatment | 21 | 1148.3 | 4.90*** | 43,018 | 2.33* |
| Error | 43 | 236 | | 18,451 | |

Codes: ns = not significant, "***" 0.001, "**" 0.01, "*" 0.05, "." 0.1.

Mean square values for relative yield under integrated nutrient management and mulching treatments at Lare and Maai Mahiu, Nakuru County, Kenya during Season 1 (September 2024-January 2025) and Season 2 (April-August 2025).

| | | Season 1 | | Season 2 | |
|---|---|---|---|---|---|
| Source of variation | Df | Ms | F-value | Ms | F-value |
| Replication | 2 | 11,371 | 2.27*** | 79,846 | 2.13** |
| Treatment | 21 | 9992 | 19.57*** | 36,734 | 0.98*** |
| Error | 43 | 511 | | 37,488 | |

Codes: ns = not significant, "***" 0.001, "**" 0.01, "*" 0.05, "." 0.1.

Mean square values for yield response under integrated nutrient management and mulching treatments at Lare and Maai Mahiu, Nakuru County, Kenya during Season 1 (September 2024-January 2025) and Season 2 (April-August 2025).

| | | Season 1 | | Season 2 | |
|---|---|---|---|---|---|
| Source of variation | Df | Ms | F-value | Ms | F-value |
| Replication | 2 | 9,611,066 | 1.07*** | 7,104,717 | 0.69*** |

**Continued**

| | | | | | |
|---|---|---|---|---|---|
| Treatment | 21 | 90,316 | 1.08** | 10,067,798 | 0.97** |
| Error | 43 | 83,526 | | 10,343,170 | |

Codes: ns = not significant, "***" 0.001, "**" 0.01, "*" 0.05, "." 0.1.

Mean square values for total crop grain yield under integrated nutrient management and mulching treatments at Lare and Maai Mahiu, Nakuru County, Kenya during Season 1 (September 2024-January 2025) and Season 2 (April-August 2025).

| | | Season 1 | | Season 2 | |
|---|---|---|---|---|---|
| Source of variation | Df | Ms | F-value | Ms | F-value |
| Replication | 2 | 752,041 | 10.21*** | 2,242,088 | 0.47*** |
| Treatment | 23 | 2,873,420 | 39.00*** | 7,861,395 | 1.64. |
| Site | 1 | 29,014,567 | 393.86*** | 58,759,764 | 12.26*** |
| Treatment × site | 23 | 405,349 | $5.50^{ns}$ | 4,337,322 | $0.91^{ns}$ |
| Error | 94 | 73,668 | | 4,793,424 | |

Codes: ns = not significant, "***" 0.001, "**" 0.01, "*" 0.05, "." 0.1.