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| ***BNJAR*** | **Blue Nile Journal of Agricultural Research (BNJAR)**  Vol. 5, Issue 2, December, 2024, pp. 43-62  Journal homepage: <https://arari.gov.et/index_bnjar.php> |

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| **Response of Tef to Nitrogen and Phosphorus Fertilizers and its Nutrient Uptake on Vertisols of Central Gondar Zone, Northwestern Ethiopia** | | |  |
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|  |  | **ABSTRACT** | |
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| **Received:** August 28, 2024  **Revised:** October 29, 2024  **Accepted:** December 21, 2024  **Available online:** December 30, 2024 |  | Tef production in Takusa and Dembia, Central Gondar Zone, suffers from poor nutrient management, as farmers apply fertilizers without understanding crop requirements, resulting in low yields. A study during the 2023/24 rainfed cropping season aimed to evaluate the effects of N & P fertilizers on tef yield and their uptake. Using a Randomized Complete Block Design with three replications, four N levels (46, 92, 138, and 184 kg ha-1) and three P2O5 levels (23, 46, and 69 kg ha-1) were tested, along with a control plot, using the improved tef variety HIBER-1. Data analysis revealed that significant effects of N on various agronomic parameters, and the interaction of NP rates affected the number of effective tillers, grain yield, harvest index, and nutrient uptake. The highest grain yield (2.01 t ha-1) was recorded in plots treated with 92 kg N ha-1 and 69 kg P2O5 ha-1. The maximum grain N uptake (44.39 kg ha-1) was also recorded at this combination, while the highest straw and total N uptake were observed with 184 kg N ha-1. Economic analysis showed that the combination of 92 kg N ha-1 and 46 kg P2O5 ha-1 provided the highest net benefit (215,220 ETB ha-1) with a marginal rate of return of 1684.97%. Therefore, it can be concluded that 92 kg N ha-1 and 46 kg P2O5 ha-1 are recommended for optimal tef yield and economic returns in these districts and other areas with similar agroecological conditions. | |
| ***Keywords:*** *Grain yield, Nitrogen, N uptake, Phosphorus, P uptake, Tef* |  |

# IntroductioN

Ethiopia is among the nations in Sub-Saharan Africa (SSA) facing significant food insecurity. Despite the country's potential richness in land resources and diverse agroecologies, agricultural productivity remains low, leading to food shortages and hunger (Abdela *et al*., 2021). Agricultural production is seriously threatened by nutrient depletion and soil deterioration (Yeshibir, 2023). Thus, enhancing agricultural productivity is a central challenge in achieving food security and reducing poverty in Ethiopia (Tamene *et al*., 2017). In the Amhara regional state of Ethiopia, where the current study was conducted, and tef is cultivated on approximately 1,177,078.03 hectares of land annually, producing an estimated 22,540,301.37 quintals. The region's average tef yield is relatively high at 19 t ha⁻¹ compared to the national average of 19.14 t ha⁻¹ (CSA, 2022). However, tef productivity remains below its potential. This is primarily due to inadequate use of synthetic fertilizers, limited application of organic residues and manure, excessive biomass removal, soil erosion, and nutrient leaching (Tesfaye *et al*., 2019).

To preserve soil nutritional quality and achieve good crop yields, the use of mineral fertilizers is essential. Nitrogen is scarce in nearly all soils, while P is deficient in approximately 70% of Ethiopian soils (Tekalign *et al*., 2001). The key constraints to improving crop yield in Ethiopia include soil nutrient depletion, low fertilizer use, and poor management practices (Tesfaye *et al*., 2021). Most Ethiopian soils have low nutrient content due to the absence of nutrient recycling (Bereket *et al*., 2019). Fertilizers are crucial inputs for maximizing crop yields, and the major tef production belts in Ethiopia indicate that N and P are the two major plant nutrients limiting tef productivity (Bereket et al., 2019). Similarly, FAO (2017) reported that declining soil fertility is the main constraint limiting food production in Ethiopia. Improving fertilizer use efficiency with a balanced mix can boost crop yield, enhance soil health, and increase fertilizer revenue (Abdisa *et al*., 2022). Multi-nutrient fertilizers are known to improve crop productivity

and nutrient use efficiency (Misgana *et al*., 2022). Likewise, balanced fertilization ensures optimal crop production, improved food quality, and benefits for growers, while minimizing nutrient losses to the environment (Gebreslasie *et al*., 2020).Tef is widely cultivated in the midland areas of the Central Gondar zone, such as the Dembia and Takusa districts. In these areas, farmers use diverse fertilizer rates without adequate evidence, resulting in under- or over-application. The deficiency of nitrogen and phosphorus is a key factor that significantly reduces tef yield. The response of tef to fertilization and the economically feasible rates of N and P for tef production have not been studied in these areas. Tef yields in these districts are low, primarily due to low soil fertility caused by poor fertilizer management (inadequate or suboptimal nutrient supply) by the farmers (Almaz *et al*., 2022). Therefore, this research was initiated to evaluate the effects of nitrogen and phosphorus rates and their uptake of tef on the Vertisols of the Central Gondar Zone, Ethiopia.

# Materials and Methods

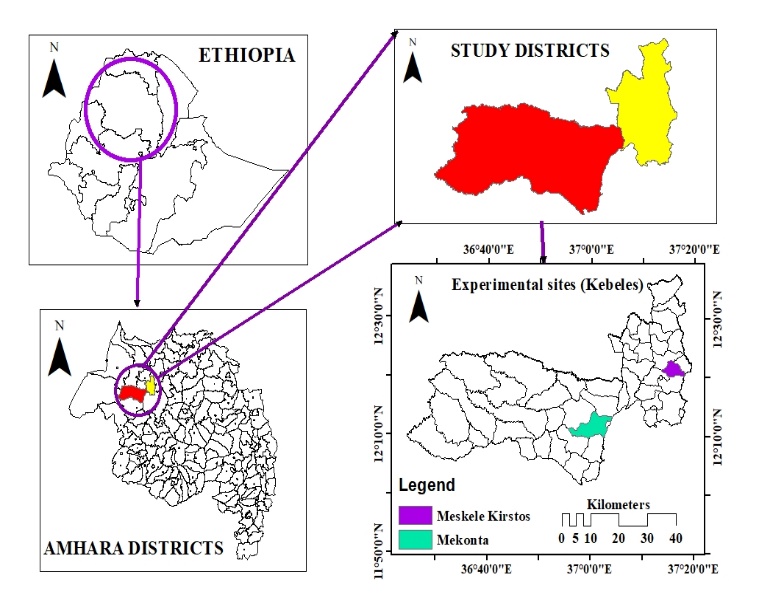
## Description of the study area

### **Geographical locations**

The field experiment was conducted during the 2023–24 main cropping season at Dembia and Takusa districts in the Central Gondar Zone, Ethiopia.

Takusa district experimental site is located at 12°11'53" N, 37°03'20" E, approximately 95 km southwest of Gondar town, 135 km northwest of Bahir Dar (the capital city of the Amhara region) and 830 km northwest of Addis Ababa.

The experimental site of Dembia district is situated at 12°19'37" N, 37°13'14" E, about 35 km northeast of Gondar, 215 km northeast of Bahir Dar, and 775 km northwest of Addis Ababa (Yonas *et al*., 2018). Both districts are located in Northwest Ethiopia.

Figure 1: Map of the study areas

### **Climatic conditions**

According to Ethiopian traditional agroclimatic zonation, Dembia and Takusa districts are classified under the mid-highland (Woinadega) agroclimatic zone, characterized by a long dry season from November to March. Both study areas exhibit a mono-modal rainfall pattern, with an extended rainy season from May to October (Yonas *et al*., 2018). The mean monthly maximum temperature in Dembia district was recorded as 31.4°C in April, with a mean monthly minimum temperature of 13.5°C in January (Fig 2). The district received a maximum rainfall of 318 mm in July and a minimum of 1 mm in March which gave a total of 1131 mm for the year 2023 (Fig 2). In Takusa district, the average daily maximum and minimum temperatures were 31.7°C in April and 13.2°C in January, respectively (Fig 3). The highest and lowest monthly rainfall recorded were 338 mm in July and 2 mm in February with a total of 1191 mm for the 2023 cropping season (Fig 3). The altitude in the Takusa and Dembia experimental sites is 1829 m and 1850 m above sea level, respectively. Long-term climatic data indicate that the highest average annual rainfall occurred in Dembia in the years 2022 (1116 mm), 2021 (1114 mm), and 2020 (1114 mm), while Takusa experienced its highest rainfall in 2022 (1188 mm), 2021 (1190 mm), and 2020 (1182 mm) (Fig 2 and Fig 3).

Source; *https://gisweb.ciat.cgiar.org*.

Figure 2: Average monthly rainfall and mean maximum and minimum temperatures at Dembia district from 2013-2022 and 2023 growing period.

Source; *https://gisweb.ciat.cgiar.org*

Figure 3: Average monthly rainfall and mean maximum and minimum temperatures at Takusa district from 2013-2022 and 2023 growing period.

### **Soils, farming systems, and crop production**

The soils are broadly categorized as Vertisols (black clay soils), Nitisols (red or reddish brown laterite soils), and intermediate soils of Luvisols (FAO, 1988). Vertisol is the predominant soil type in both Dembia and Takusa districts, which have a large ability to store water but water logging problems, occur in areas where the land slope is less than 8% (Tsedalu et al., 2018). The majority of people in the study districts rely on a mixed agricultural system. The locations represent the major tef-producing agroecologies of the region. The study areas have a high potential for cereal crops, legumes, and spice crops production. The major crops cultivated in the districts include Finger millet (*Eleusine coracana (L.) Gaertn*), Tef (*Eragrostis tef (Zucc.)Trotter*), Sorghum (*Sorghum bicor L. Moench)*, Maize (*Zea mays*), Chickpea (*Cicer arietinum*), and Black and White cumin (*Nigella sativa*). The traditional rain-fed agricultural practices, which used oxen to prepare the field for crop production, is common in the districts of Dembia and Takusa (Yonas *et al*., 2018).

## Experimental Materials, Treatments, and Design

As fertilizer sources for N and P, urea (46% N) and Triple Super Phosphate (TSP) (46% P2O5) were used, respectively. Improved tef (Eragrostis Tef/Zucc./Trotter) Hibber-1 variety at a seed rate of 15 kg ha-1 was used as a test crop. The variety was selected based on yield, disease resistance, and farmers' acceptance in the study areas. Hibber-1tef variety was released in 2017 for the optimum moisture areas (high potential tef-producing areas) of the country. It performs very well in areas having an altitude of 1700-2400 m and annual rainfall of 500-1000 mm. The seed was obtained from the Adet Agricultural Research Center (AARC) (Worku *et al*., 2018). The treatments comprise factorial combinations of four levels of N (46, 92, 138, and 184 kg N ha-1) and three levels of P (23, 46, and 69 P2O5 kg ha-1). One additional satellite treatment (0, 0) was used for economic and nutrient uptake. A total of 12 N and P combination treatments were studied in a factorial Randomized Complete Block Design (RCBD) with three replications. The gross plot size is 3 m x 2.5 m length (7.5 m2) with 15 rows and the net plot size is 2 m x 2.5 m length (5 m2) with 10 rows. Blocks, plots, and rows were spaced 1.5 m, 1 m, and 0.2 m apart, respectively.

## Experimental Procedures

Before planting, the land was prepared with oxen-drawn plows and leveled by hand under the traditional tillage method. Consequently, the field was plowed three times, and the final plowing was conducted according to farmer practice just before planting. After seedbeds were prepared, seeds were manually drilled. The date of planting on both districts was 1 August 2023. All dose of P for each treatment was applied at planting while N fertilizer was applied in two splits, (the first 1/2 was applied at sowing, and the remaining at the tillering stage). Hand weeding was done at early tillering, mid-tillering, and before heading. Insects, pests, and disease occurrences were managed during the crop-growing season. Harvesting was done manually using hand sickles at the harvesting stage.

## Soil Sampling Techniques and Analysis

Representative soil samples were collected before planting to determine the initial fertility status of the experimental site. Soil samples were collected in a zigzag manner from 0-20 cm depth using auger. To form a single composite soil sample, a total of 13 soil sub-samples were collected per site from different spots. The soil samples were air dried on shelves, ground by using a pestle and mortal, and screened through a 2 mm and 0. 5 mm (for total N and organic carbon (OC) determination) sieve. The major soil physicochemical properties that were analyzed in the Gondar Soil Testing Laboratory include texture, pH, organic carbon (OC), total N, available P, exchangeable bases, and cation exchange capacity (CEC). Soil textural analysis was conducted using the Bouyoucos hydrometer technique (Bouyoucos, 1962). The pH of the soil was measured using a glass electrode connected to a digital pH meter, and the ratio of soil to water was found to be 1:2.5 (mass/volume) (Chopra and Kanwar, 1976). Cation exchange capacity (CEC) was assessed following soil saturation with ammonium acetate (NH4OAC) and displacement using NaOAC (Chapman, 1965). The Walkley-Black extraction and titration method was used to analyze the soil OC content (Walkely and Black, 1934). The Micro-kjeldhal digestion technique was used to analyze total N (Jackson, 1973). The Olsen extraction approach was used to analyze available P (Olsen et al., 1954) and measured by spectrophotometer.

## Plant Tissue Sampling and Analysis Methods

Representative tef grain and straw samples were collected at physiological maturity, oven-dried at 65°C for 24 hours, milled, and sieved to 1 mm. These samples were analyzed for nitrogen (N) and phosphorus (P) concentrations at the AARC laboratory using wet digestion. Total N concentrations of grain and straw were determined using the modified Kjeldahl method (Jackson, 1958). Phosphorus in plant tissue was determined by the Vanadomolybdate method (Estefan *et al*., 2013), and the P concentration was measured by UV-VIS spectrophotometer at 660 nm. The N and P concentrations in grain and straw were used to compute the N and P uptake, which was derived by multiplying the yields (grain and straw) per hectare by the corresponding nutrient content according to Temesgen *et al*. (2021)..

Grain/straw uptake of N (kg ha-1) =(Yield of grain/straw (kg ha-1)×N con of grain/straw(%))/100)

Grain/straw uptake of P (kg ha-1) =(Yield of grain/straw(kg ha-1)×P con of grain/straw(%))/100)

## Data Collection and Analysis

### **Agronomic data**

Days to 90 % physiological maturity were determined by counting the days from planting to the date when 90% of the peduncle turns to yellow. It was recorded when no green color remains on the glumes and peduncles of the plant. Plant height (cm) was measured from the ground to the tip of the spike of 10 randomly selected plants from the central rows at physiological maturity and the average was recorded as plant height (cm) per plant. Panicle length (cm) is the length of the panicle from the node where the first panicle branches emerge to the tip of the panicle. It was measured by an average of 10 randomly selected plants. Number of productive tillers per plant was counted from tillers producing filled panicles of ten randomly selected plants on the mid-portion of each plot. Above-ground biomass yield (t ha-1) was calculated by gathering all of the plant material from the net plot, including the leaves, stems, and seeds. The material was then sun-dried until a consistent weight was reached, weighed, and converted to ton ha-1. Grain yield (t ha-1) was measured from the grains harvested from the net plot area after threshing and sun-drying and adjusted by 12.5 % moisture content. It was converted to grain in ton ha-1. Adjusted grain yield=Actual grain yield\*((100-Actual moisture content)/ (100-Standard moisture content)) (Mulvaney and Devkota, 2020). Straw yield (t ha-1) was measured after threshing and measuring the grain yield by subtracting the grain yield from the dry biomass yield. Harvest Index (%) was determined by dividing the grain yield by the total above-ground biomass yield and then multiplying by 100. Thus, harvest index= (Grain yield (t ha-1))/ (Aboveground biomass yield (t ha-1))\*100 (Mesenbet, 2021). Lodging percentage or lodging degree was evaluated shortly before harvest through visual inspection, utilizing a scale ranging from 1 to 5. Here, 1 (0-15 degrees) signifies no lodging, 2 (15-30 degrees) indicates 25% lodging, 3 (30-45 degrees) signifies 50% lodging, 4 (45-60 degrees) indicates 75% lodging, and 5 (60-90 degrees) signifies complete 100% lodging (Donald, 2004). The scales were assessed lodging based on the angle of inclination of the main stem from the vertical line to its base through visual observation. The lodging percentage data was subjected to an arcsine transformation, following the method described by Gomez and Gomez (1984).

## Data analysis

Before the combined analysis, a homogeneity test was done using a general linear model. Data from the two sites were collected independently, the homogeneity of variance was evaluated, and the calculated value was compared to the tabulated value. Following this, data from the two locations were compared about the treatments applied at each location. F- Test was used to test homogeneity error of variance using the following equation,

(Gomez and Gomez, 1984). If F- calculated < F- tabulated the data is homogenous.

All agronomic and soil data were collected properly managed and analyzed ANOVA using General Linear Model on SAS version 9.4 (SAS, 2016). The mean separation was computed using LSD at a 5 % probability level. Pearson correlation coefficient was conducted to conclude relations between yield and yield-related traits of tef as influenced by NP fertilizer rate.

## Partial budget analysis

Partial budget analysis was carried out using the CIMMYT partial budget approach (CIMMYT, 1988). For the computation, the average price of the inputs (fertilizers) and output (grains and straw yield) were noted. Because they were very equal for all treatments, all expenses were computed without taking into account the cost of additional agronomic operations, such as seed, land plowing, planting, weeding, protecting the farm, and harvesting except fertilizer application. Each cost and profit was expressed on a per hectare basis and measured in Ethiopian Birr (ETB). To represent the actual farmer yield expected under production management conditions, the grain and straw yield of tef was adjusted to 10% lower. The sale price of urea fertilizer is ETB 40 kg-1 and for the case of Triple super phosphate (TSP), the cost of NPS fertilizer is ETB 40 kg-1 (considered as the cost of TSP). Only application costs and prices of N and P were taken as variable costs. At Dembia and Takusa districts, the price of tef grain and straw yield was ETB 100 kg-1 and ETB 8 kg-1 respectively during 2023 at harvest and changed into hectare basis and cost of fertilizer application ETB 200 per man day ha-1 on both districts. Following CIMMYIT's partial budget procedure, total variable cost (TVC), Gross benefit (GB), and Net benefit (NB) were calculated. The treatments were arranged in the order of increasing TVC and dominance analysis was done to exclude dominated treatments from the marginal rate of return (MRR) analysis. A treatment is said to be dominated if it has a higher TVC than the treatment which has a lower TVC next to it but has a lower NB. A treatment that is non-dominated having an acceptable MRR value (greater than 100%) and having the maximum NB is said to be economically profitable. The following equations were used.

(CIMMYT, 1988).

Where, MRR (%) = Marginal Rate of Return, ΔNR= Change in Net Benefit, ΔTVC= Change in Total Variable Cost, GB= Gross Benefit, TVC= Total Variable Cost, AGY= Adjusted Grain Yield, UGY= Unadjusted Grain Yield.

# Results and Discussion

## Soil Physicochemical Properties before Planting

As indicated in Table 1, the soils of the experimental sites were clay in texture with the proportion 0.72% Sand, 13.28% Silt, and 86% Clay at Dembia and 6.72% Sand, 17.28% Silt, and 76% Clay at Takusa Districts. Clay contains mineral nutrients and holds water better than other soil types which gives an advantage to plants cultivated in this type of soil (Chuasiriporn, 2017). The organic carbon (OC) content of experimental sites at Dembia and Takusa districts was 1.41 and 2.01%, respectively, which was in the very low range (Hazelton and Murphy, 2007). This might be due to continuous tillage and crop residue removal from the farmland (Berhanu, 2016). The soil reaction for Dembia (6.78) and Takusa (6.74) sites was neutral (FAO, 2004) (Table 1). This indicates that the soils of both sites are favorable for plant growth. Some previously conducted experiments also proved that most crops grow best when the soil pH is between 6.0 and 8.2 (Horneck *et al*., 2011; FAO, 2004). The total nitrogen (TN) content in Dembia (0.090%) and Takusa (0.091%) sites was very low as per the ratings of Landon (2014). Tef is a highly demanding crop for N and the production potential of tef is highly affected by N deficiency. Similar results were reported by Teshome et al., (2019) associating the low N content in Vertisols with leaching or denitrification, and mobility of N in the soil as these soils have higher water retention capacity in the rainy seasons. According to Teshome *et al.*, (2021), most of the Ethiopian Vertisols are N-depleted, and more than 50% of the cultivated lands are N-responsive soils. Hence, the suggested ideal TN level required for crop production is 0.2% (EthioSIS, 2013).

Available phosphorus (Av. P) was medium at Dembia (7.45 ppm) and high at Takusa (12.43 ppm) (Horneck *et al*., 2011). The higher available phosphorus (Av. P) content at the Takusa site could be attributed to the application of P fertilizers during the cultivation of various crops, as indicated by the land use history, with pepper being the precursor crop at the experimental site. The farmers used a high amount of NPS fertilizer in the Takusa districts to get a high pepper yield. In addition; the higher clay content in both sites could be a factor since clay soil particles usually have higher P retention capacity because of their large surface area per unit volume (Prasad and Chakrabort, 2019).

In Dembia and Takusa experimental sites, the cation exchange capacity (CEC) was 78.86 and 71.21 cmol (+) /kg, respectively. This CEC of both of the experimental sites was rated as very high based on Hazelton and Murphy`s (2007) ratings. The higher CEC in the soils of both sites could be associated with the higher levels of clay that increase the negative surface charges and nutrient-holding capacity of the soil which in turn enhances soil fertility. This result was supported by Fisseha *et al.,* (2003) who stated that higher CEC values in Vertisols are due to higher clay content. As a result, this soil has a greater capacity for adsorbing basic cations like Ca, K, and Mg.

**Table 1; Physicochemical properties of the study area soils**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Parameters | Dembia | | Takusa | | References |
| Value | Ratings | Value | Ratings |
| Soil pH (H2O) | 6.87 | Neutral | 6.74 | Neutral | Hazelton and Murphy (2007) |
| Total N (%) | 0.09 | Very low | 0.09 | Very low | Landon (2014) |
| Ava. P (ppm) | 7.45 | Medium | 12.63 | High | Horneck *et al*. (2011) |
| OC (%) | 1.41 | Very low | 2.02 | Very low | Hazelton and Murphy(2007) |
| CEC ((cmol(+)/kg) | 78.86 | Very high | 71.24 | Very high | Hazelton and Murphy (2007) |
| Physical properties |  |  |  |  |  |
| Sand (%) | 0.72 |  | 6.72 |  |  |
| Silt (%) | 13.28 |  | 17.28 |  |  |
| Clay (%) | 86 |  | 76 |  |  |
| Textural class | Clay |  | Clay |  | FAO (2006) |

## Phonological and Growth Parameters

### **Days to 90 % physiological maturity**

The combined ANOVA results showed that the main effects of N (p≤0.001) fertilizer rates were highly significant affected on the physiological maturity of tef. The longest 82.94 days to reach 90% maturity were recorded from the plot received 184 kg N ha-1. On the other hand, the shortest 78.11 days required to reach 90% maturity were observed on the plot received 46 N kg ha-1 (Table 2). The maturity of tef increases with increasing N levels. The rates of N increasing from 46 kg ha-1 to 138 kg N ha-1 prolonged days to maturity by about 4.8 days. This might be attributed to the formation of chlorophyll which keeps the plant photosynthetically active for a longer period (Tamirat, 2021). The results agree with other findings that the application of a high rate of N delayed maturity in tef was significant with the increase in N rates (Temesgen, 2001; Abraha, 2013; Fenta, 2018; Tekulu *et al*., 2019; and Yohanis *et al*., 2020). This result is also coherent with the outcome of Fenta (2018) who found that high N application rates caused physiological maturity to be delayed due to the direct effect of N on vegetative growth in tef. In contrast to the current findings, Getahun *et al*., (2018) and Teshome *et al*., (2019) described that the application of different rates of N fertilizer has no significant effect on the days to maturity of tef.

### **Plant height**

The ANOVA results over two sites showed that the main effects of N (p≤0.001) and phosphorous (p<0.05) fertilizer rates were showing highly significant and significance differences (p<0.05) respectively in plant height. The longest plant height (130.66) was recorded at the highest N rate of 184 N kg ha-1 whereas the shortest plant height was recorded at the lowest (112.79) N rate of 46 N kg ha-1 followed by the control plot (75.95) (Table 2). This might be explained by the reality that N typically promotes tef vegetative development, which occurs in the higher status of the plants with the greatest plant height. Thus, with a further increase in the N treatment rate, the tef plants reached a much higher maximum plant height. Consistent with this finding, Ekero *et al*., (2021) stated that the maximum possible N rate was used to produce tef with a higher plant height. Similarly, Tamirat (2021), showed that the main effects of N rates had a highly significant (p≤0.001) effect on the plant height of tef. Also, Fenta (2018) noted that tef treated with greater N fertilizer rates at 92 kg ha−1 had a mean height of around 112.6 cm, which was followed by 107.7 cm at 69 kg ha−1, making them taller than the plants treated with lower N fertilizer rates. The mean plant height of tef was 94.8 with the application of higher rates of N at 66 kg N ha-1 rates followed by 93.3 cm at 50 kg N ha-1 as compared to the lower N fertilizer rates. Significantly lower plant heights of 89.6 and 90.6 cm of tef were recorded on the control plot and 18 kg ha-1, respectively (Yohanis *et al*., 2020). In contrast with this result, increasing levels of N fertilizer application did not significantly enhance the plant height of tef (Temesgen, 2001). Regarding P2O5, the highest (125.29) plant height was found from the application of 46 kg P2O5 ha-1 which was statistically similar to 69 kg P2O5 ha-1. The lowest (123.46) plant height was obtained from the application of 23 kg P2O5 ha-1. A similar result was found by Ewunetie *et al*., (2024) who reported that the maximum plant height due to P fertilizer was found with the application of 46 kg P2O5 ha-1, which was statistically equivalent to the application of 23 P2O5 ha-1.

Table 2; Main effects of N and P2O5 rates on phonological and growth parameters of tef

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| N (kg ha-1) | DTM | PH(cm) | PL(cm) | LI (%) |
| 46 | 78.11b | 112.79d | 48.47c | 40.67d |
| 92 | 78.72b | 125.07c | 52.30b | 60.50c |
| 138 | 79.00b | 129.36b | 53.79ab | 70.06b |
| 184 | 82.94a | 130.66a | 54.28a | 73.83a |
| LSD (0.05) | 3.01\*\* | 1.29\*\* | 1.79\* | 2.33\*\* |
| P2O5  (kg ha-1) |  |  |  |  |
| 23 | 80.79 | 123.46b | 52.01 | 59.46b |
| 46 | 79.38 | 125.29a | 52.18 | 61.42ab |
| 69 | 78.92 | 124.67a | 52.45 | 62.92a |
| LSD (0.05) | 2.61ns | 1.12\* | 1.55ns | 2.02\* |
| CV (%) | 2.64 | 3.47 | 4.43 | 5.67 |
| Control | 85.75\*\* | 75.95\*\* | 30.13 | 20.5 |

Where, PH= Plant Height (cm), PL= Panicle Length (cm), HI= Harvest Index (%), LSD= Least Significant Difference at a 5% level; CV= Coefficient of Variation, \*= Significant (5%), \*\*= Highly Significant (1%), NS= non -significant. At a 5% level of significance, there are no significant differences in means across columns and rows with the same letters.

### **Panicle length**

One of the yield characteristics that affect grain production is panicle length. Grain yield may be increased in crops with longer panicles. The combined ANOVA results indicated that the main effect of nitrogen (N) had a highly significant impact (p≤0.001) on the panicle length of tef. Similar to plant height, an increase in the rate of N application increased the panicle length of the tef. The maximum panicle length of 54.84 cm was recorded at the highest nitrogen application rate of 184 kg N ha⁻¹, whereas the shortest mean panicle length of 48.47 cm was observed at the lowest nitrogen rate of 46 kg N ha⁻¹ (Table 2). Taller tef plants typically have longer panicles because of their favorable vegetative development, which is facilitated by high nitrogen levels that play a crucial role in the construction of chlorophyll. The effect of excessive N treatment on tef production was shown to be caused by the significant influence of panicle length on grain yield. The present finding is in line with Getahun *et al*., (2017); Tamirat (2021); and Merdikios *et al*., (2022) tef plants with higher panicle length were found by applying a high amount of N fertilizer due to high nitrogen usually favoring vegetative growth of tef, which results in relatively greater panicle length. Similarly, Getahun *et al*., (2018) and Yared *et al*., (2019) mentioned that the length of the panicle increased with increasing nitrogen, and thus, crops with longer panicles yielded considerably more grain, straw, and total biomass than those with smaller panicles. This current result is similar to the findings of Mulugeta (2003); Legesse (2004); Mitiku (2008); Haftamu *et al*., (2009); Giday *et al*., (2014); and Yared *et al*., (2019) reported that a positive and significant increase in panicle length was observed with the rising nitrogen fertilizer rates on tef. The current finding contradicts the result of Teshome *et al*., (2019) who showed that panicle length increased significantly with nitrogen fertilizer treatment up to 92 kg ha-1; however, further increases in nitrogen fertilizer rates did not consistently result in longer panicle lengths.

### **Lodging index (%)**

The lodging index was highly significantly (p≤0.001) and significantly (p<0.05) affected by the main effect of N and P respectively. The highest (73.83 %) lodging index was found from N fertilized with 184 kg N ha-1. The lowest (40.67 %) LI was recorded from the lowest N fertilized with 46 kg ha-1 and the control plot (Table 2). When fertilizer was added, the lodging index of tef was also raised. This might be the result of the tef's succulent stem elongation, rapid vegetative growth, and plant height were all improved by an increase in the rate of total nitrogen. The reason for the rising lodging index in response to more N fertilizer might be attributed to the plants' increased height, which was caused by an abundance of nutrients (Yared *et al*., 2019). The lowest tef LI was achieved with a decreased fertilizer application rate. Tef is very susceptible to lodging because of excessive soil N or exogenous N treatment (Ekero *et al*., 2021). The current result is in line with Tekalign et al., (2000) who obtained the addition over the rates of 60 N kg ha-1 responses to a significant effect in LI percentage of tef. Similarly, Yared *et al*., (2020) found that applying 69 kg N ha-1 produced the highest lodging index (66.67%), while the control plot produced the lowest lodging index (33.33). In addition, Brady and Weil (2002) reported that the over-application of N results in increased vegetative growth and stem cell expansion, which weakens the stem to be affected by lodging. Abraha (2013) indicated that excessive rates of nitrogen fertilizer application are thought to be the cause of lodging in cereals.

Regarding phosphorus, the highest lodging percentage of 62.92 % was found from the application of 69 kg P2O5 ha-1 while the lowest 59.46 % was obtained from the plot receiving 46 kg P2O5 ha-1 (Table 2). This result was confirmed by Yared *et al*., (2020) the highest lodging index 70.83% was observed with the application of 150 kg ha-1 blended fertilizer while the lowest 31.25%, was recorded in the control plot. This finding aligns with Teshome (2019) who reported the highest lodging of tef (38.92%) at the same 150 kg ha-1 blended fertilizer rate. Similarly, Shiferaw (2012) noted the highest lodging of tef (74%) was found at a N/P2O5 rate of 64/46 kg ha-1. Additionally, Fayera *et al*., (2014) reported that the highest lodging percentage of tef (79.74%) was observed with the application of the highest NPK rate, specifically 138 kg N ha-1 combined with 55 kg P ha-1 and 0 kg K2O ha-1. While lodging does not significantly affect the overall biomass production, it is known to result in significant economic losses due to decreased grain and straw yield and quality, especially for small grains like tef. On average, lodging accounted for 11-22% of the total losses in grain yield (Seyfu, 1983). Both internal and external elements, including wind, rain, and crop morphological characteristics, as well as their interactions, may cause lodging.

## Yield and Yield Related Components

### **Number of productive tillers per plant**

The ANOVA results indicated that the number of productive tillers per plant was significantly affected by the interactions of N and P fertilizers (p<0.05). The highest number of fertile/productive tillers per plant (4.87) was observed at the combined application of 46 kg P2O5 ha-1 and 92 kg N ha-1 while the lowest (3.15) was found on plot received 23 kg P2O5 ha-1 and 46 kg N ha-1 and the control plot (Table 3). This might be due to insufficient N and P stunt plant growth, causing the plant to allocate resources to existing tillers rather than producing new ones. Weaker plants also face increased competition for light, water, and nutrients, further limiting tiller development. Feyera (2014) revealed that the crop's increased supply of N during its vegetative growth phase promotes tillering. Consistent with this result, Haftamu *et* *al*., (2009) and Tekalign et al., (2000) reported that in response to the number of tillers on tef, the addition of the N rate had a significantly higher reaction. The current result is in line with Yared *et**al*., (2019) who reported that the maximum number of tillers was recorded with the addition of 92 kg N and 46 kg P2O5 rate ha-1 on tef. In contrast with the result of this study, Alemu *et al*., (2016) reported that the number of effective tillers and the trend of growing or declining in the tef were unaffected by the amounts of compost and NP fertilizer.

**Table 3: Interaction effect of N and P2O5 rates on effective tillers per plant of tef.**

|  |  |  |  |
| --- | --- | --- | --- |
| **N rates**  **(kg ha-1)** | **P205 rates (kg ha-1)** | | |
| 23 | 46 | 69 |
| 46 | 3.15f | 3.53e | 4.28c |
| 92 | 3.62e | 4.87a | 4.58b |
| 138 | 3.62e | 3.70e | 4.12cd |
| 184 | 3.62e | 3.68e | 4.05d |
| LSD (0.05) |  |  | 0.23\* |
| CV (%) |  |  | 6.65 |
| Control |  |  | 1.6 |

Where, LSD= Least Significant Difference at 5% level; CV= Coefficient of Variation, \*= Significant (5%), \*\*= Highly Significant (1%), NS= Non -significant. At a 5% level of significance, there are no significant differences in means across columns and rows with the same letters.

### **Biomass yield**

The main effects of N and P fertilizer rates had highly significant (p≤0.001) and significant (p<0.05) effects, respectively, on the mean biomass yield of tef. The highest (9.75 t ha-1) biomass yield of tef was recorded from the application of 184N kg ha-1. The lowest value (1.96 t ha-1) was recorded from the control plot (Table 4). A significant difference was not seen between the N rates of 92 and 138 kg ha-1. Tef biomass yield was consistently increased with an increase in the rates of N fertilizer. In general, a rise in N rates enhanced the biomass yield of tef. This might be due to increasing nitrogen (N) boosting the biomass yield by supporting vegetative growth, protein synthesis, chlorophyll production, and overall plant development. Consistent with this result, Girma *et al*., (2021) reported that increased N application rates resulted in a substantial increase in above-ground biomass. Likewise, Teshome *et al*., (2019); Yohanis *et al*., (2020); and Tamirat (2021) reported that the largest biomass yield was recorded at the maximum rate of N. Studies by Legesse (2004); Mitiku (2008); and Haftamu *et al*., (2009) similarly revealed that higher overall biomass production was achieved with additional increases in N. Increased assimilate investment in leaves and stems, which ultimately results in a rise in dry matter production, maybe the cause of the higher above-ground dry biomass yield recorded from higher N amounts (Teshome *et al*., 2019). This might be due to better crop growth rate, leaf area index, and accumulation of photo-assimilate due to the maximum number of days to maturity by the crop, which ultimately produced more biomass yields (Melkamu *et al*., 2022 ). Similarly, Tamirat (2019) reported that the increase in biomass yield might be attributed to high N application, which favorably stimulates rapid vegetative growth and stem cell enlargement, both of which increase biomass yield. Regarding P, the highest (8.02 t ha*-*1) biomass yield of tef was recorded from the application of 69 kg P2O5 ha-1. The lowest (7.59 t ha-1) was recorded on the lower P fertilizer rates of 23 kg P2O5 ha-1 which is statistically at par with 46 kg P2O5 ha-1 followed by the control plot (1.96 t ha-1) (Table 4). The biomass yield of tef was increased with increasing P fertilizer rates (Table 4). The biomass yield of tef was positively and significantly correlated with P (Chala, 2021). Girma *et al*., (2021) also indicated that the growth in total biomass correlated with P rates. The present finding is supported by Suleyman (2021) who stated that the maximum above-ground biomass yield was recorded at the rate of 69 kg P2O5 ha-1. Similarly, Chala (2021) observed that a mixture of N and P gave the highest biomass yield of tef when 69 kg of each of N and P ha-1 was applied.

Table 4: Main effects of N and P2O5 rates on biomass and straw yield of tef.

|  |  |  |
| --- | --- | --- |
| N rates | BMY | STY |
| 46 | 4.95c | 3.55c |
| 92 | 8.22b | 6.34b |
| 138 | 8.41b | 6.75b |
| 184 | 9.75a | 8.27a |
| LSD (0.05) | 0.38\*\* | 0.43\*\* |
| P2O5  rates |  |  |
| 23 | 7.59b | 6.17 |
| 46 | 7.88ab | 6.36 |
| 69 | 8.02a | 6.15 |
| LSD (0.05) | 0.37\* | 0.33ns |
| CV (%) | 10.33 | 13.25 |
| Control | 1.96 | 1.54 |

Where, BMY= Biomass yield (t ha-1), STY= Straw yield (t ha-1), LSD= Least Significant Difference at 5% level; CV= Coefficient of Variation, \*= Significant (5%), \*\*= Highly Significant (1%), NS= non -significant. At a 5% level of significance, there are no significant differences in means across columns and rows with the same letters.

### **Straw yield**

The ANOVA results over two locations indicated that the straw yield of tef was highly significantly (p≤0.001) affected by the main effects of N. The highest straw yield (8.27 t ha-1) was observed from plots that were supplied with 184 kg N ha−1 while the lowest straw yield (1.54 t ha-1) was obtained from the control plot (Table 4). This is why the control plots without added nitrogen often experience nutrient deficiencies that hinder photosynthesis and vegetative growth, leading to reduced straw yield due to stunted development and fewer tillers. Similar to the findings of this investigation, Tamirat (2021) found that the highest straw yield was observed in response to applying the highest N rates. Likewise, Rahman *et al.*, (2000) and Tamirat (2019) observed that N affected the number of tillers and plant height during vegetative growth, leading to an increase in the yield of straw. When high N fertilizer is applied, the amount of straw produced may increase because more plants can readily access and absorb the nutrient, which leads to vigorous vegetative growth with more leaf area. This increases the amount of assimilated production, photosynthesis, and dry matter accumulation (Islam *et al*., 2008; Tamirat, 2019; and Yohanis *et al*., 2020). Similarly, the main effects of applying higher rates of N fertilizer had a highly significant influence on the straw yield of tef, and this yield raised as the rates of N fertilizer increased (Alemu *et al.*, 2016)

### **Grain yield**

The ANOVA results indicated that the interaction effects of N and P fertilizer rates had a highly significant (p≤0.001) effect on grain yield. The highest grain yield (2.01 t ha-1) was achieved at the combined rate of 92 kg N ha-1 with 69 kg P2O5 ha-1, while the smallest (0.41 t ha-1) was observed from the control plot (Table 5). This is because control plots typically lack fertilizer application, leading to deficiencies in essential nutrients such as N and P, which are crucial for healthy tef growth and achieving high yields. Furthermore, applying 92 kg N ha-1 of N fertilizer increased grain yield significantly, but increasing the rates of N fertilizer further decreased grain yield (Table 5). This might be due to an optimum rates mismatch between the availability of sufficient amounts of the nutrient in the soil and the plant's need for uptake. Since most soils have low total N contents, a high reaction to N makes sense. Ekero *et al*. (2021) found that higher nitrogen application rates resulted in reduced yields. This is most likely due to lodging, which might have been produced by excessive N at higher rates. Conversely, tef grain production was lower when the maximum N and P rates are combined (Table 5). The reason for this might be an excess of the nutrient that encourages increased vegetative development of plant parts, which results in lodging before the transmission of dry matter to grain (Yared *et al*., 2019). Tagesse *et al*. (2018) found that the best grain production was attained at 200 kg blended NPS ha-1 supplemented with 92 kg N ha-1, which is similar to this result. According to Teshome *et al*., (2019), the combined rates of 92 kg N and 100 kg ha-1 blended fertilizer produced the maximum grain production (2002.5 kg ha-1). The current finding in line with Alemu *et al*., (2016) who found that tef' grain yield increased as NP fertilizer application rates increased.

### **Harvest index**

Analyzing the harvest Index (HI) is crucial because it offers valuable insights into how efficiently a plant converts the energy and nutrients it absorbs into the harvestable parts of the crop, such as grains, fruits, or seeds. The ANOVA results indicated that the interaction effects of N and P had a significant (p≤0.05) influence on the tef harvest index. The maximum harvest index (35.78%) was recorded at the combined application of 46 kg N ha-1 with 69 kg P2O5 ha-1. The minimum (14.86%) was obtained from the combined rate of 184 kg N ha-1 with 46 kg P2O5 ha-1; which is statistically not different from the rates of 184 kg N ha-1 with 69 kg P2O5 ha-1. When the greatest N rates were applied, the tef harvest index decreased (Table 5). This is due to excess nitrogen levels can promote dense canopy growth, which may result in shading of the lower leaves and reproductive structures. This shading reduces the photosynthetic efficiency in these areas, limiting the energy available for grain or fruit development, and ultimately reducing the harvest index. In line with this result, Girma *et al*., (2021) indicated that the harvest index decreased as N rates increased over 46 kg ha-1. The current result supported by the findings of Teshome *et al*., (2019) reported as N and blended fertilizer levels increased, a greater grain yield with a comparable rise in straw production contributed to an increase in the harvest index. Tagesse *et al*., (2018) also indicated that the harvest index was significantly affected by the interaction between blended NPS and additional N rates on wheat. The tef harvest index is often lower than other small grain cereals (Ekero *et al*., 2021).

Table 5; Interaction effect of N and P2O5 rates on grain yield (t ha-1) and harvest index (%) of tef.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| N  (kg ha-1) | P205  (kg ha-1) | | GY  (t ha-1) | HI  (%) |
|  | 23 | | 0.89f | 19.12ef |
| 46 | 46 | | 1.54cde | 30.11b |
|  | 69 | | 1.76bc | 35.78a |
|  | 23 | | 1.66cde | 20.78de |
| 92 | 46 | | 1.97ab | 23.31cd |
|  | 69 | | 2.01a | 24.96c |
|  | 23 | | 1.63cde | 19.58def |
| 138 | 46 | | 1.68cd | 19.32def |
|  | 69 | | 1.67cd | 20.61de |
|  | 23 | | 1.51de | 16.36fg |
| 184 | 46 | | 1.44e | 14.86g |
|  | 69 | | 1.49de | 14.91g |
| LSD (0.05) | |  | 0.22\*\* | 4.02\*\* |
| CV (%) |  | | 10.17 | 14.65 |
| Control |  | | 0.41 | 21.14 |

Where, GY= Grain yield, HI= Harvest index, LSD= Least Significant Difference at 5% level; CV= Coefficient of Variation, \*= Significant (5%), \*\*= Highly Significant (1%), NS= non -significant. At a 5% level of significance, there are no significant differences in means across columns and rows with the same letters.

## Nutrient Uptake by Grain and Straw

### **Nitrogen uptake by grain and straw**

The ANOVA results revealed that grain N uptake was significantly (p<0.05) affected by the interaction between N and P rates. The highest grain nitrogen uptake (44.39 kg ha-1) was recorded with 92 kg N and 69 kg P2O5 ha-1, while the lowest uptake (7.42 kg ha-1) was from the control plot. This is because control plots have a limited supply of bioavailable nitrogen in the soil. Without the addition of fertilizers to enhance this supply, plant growth, and nitrogen uptake remain restricted. An increasing trend in grain N uptake was observed up to the application rates of 92 kg N and 46 kg P2O5 ha-1, and 92 kg N and 69 kg P2O5 ha-1, respectively (Tables 7). Grain N uptake is positively correlated with economic yield. Therefore, the treatment that resulted in the highest economic yield (92 kg N and 69 kg P2O5 ha-1) showed no significant difference in grain N absorption compared to the plots that received 92 kg N and 46 kg P2O5 ha-1. These results align with Sheoran *et al*. (2015), who reported that the combined use of nutrients resulted in superior N grain uptake compared to their individual use. Increased nutrient uptake is likely due to a balanced supply of nutrients and a well-developed root system facilitating better absorption of water and nutrients (Devi *et al.,* 2011 and Singha *et al*., 2011). The ANOVA results revealed that straw and total N uptake was highly significantly (p≤0.001) affected by the application N rates. The highest straw (72.5 kg ha-1) N uptake was recorded from the plot receiving 184 kg N ha-1, while the lowest straw (14.84 kg ha-1) N uptake was observed in the control plot (Table 6). These results indicated that straw N uptake increases with higher N levels, showing a positive response to N fertilizer. This is likely due to relatively higher straw yield and straw N concentration, which resulted in increased N uptake by straw. This finding is consistent with Bereket *et al*., (2018), who reported that straw N uptake in wheat increased with higher nitrogen rates. The maximum total nitrogen uptake (112.59 kg ha-1) was recorded from the plot receiving 184 kg N ha-1, while the minimum total nitrogen uptake (22.27 kg ha-1) was observed in the control plot (Table 6). The result indicated that total N uptake increases when N rates increase. This might be when more nitrogen is applied to the soil, and the concentration of available nitrogen forms (e.g., nitrate (NO3−) and ammonium (NH4+) in the soil solution increases. This raised availability enhances the rate at which plant roots can absorb N. In addition, increased N supply stimulates photosynthesis and growth, leading to higher biomass production. Since N uptake is proportional to biomass, plants with more roots and shoots absorb more nitrogen. The application of NP fertilizers has improved total N uptake by 19.8% over the plot receiving no fertilizer. This result is similar to Redai *et al*., (2018) observed that total nutrient uptake significantly increased with nutrient application, while the control group exhibited low nutrient uptake.

Table 6; Main effects of N and P2O5 rates on nutrient uptake by straw yield

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| N (kg ha-1) | SNU  (kg ha-1) | SPU  (kg ha-1) | TNU  (kg ha-1) | TPU  (kg ha-1) |
| 46 | 18.09d | 3.24b | 42.29d | 7.66c |
| 92 | 43.19c | 7.40a | 83.27c | 12.94bc |
| 138 | 59.2b | 8.52a | 96.09b | 13.46ab |
| 184 | 72.5a | 8.24a | 112.59a | 16.29a |
| LSD (0.05) | 12.75\*\* | 2.66\* | 16.44\*\* | 3.12\* |
| P2O5 (kg ha-1) |  |  |  |  |
| 23 | 45.49 | 6.59 | 77.26 | 12.08 |
| 46 | 46.96 | 6.51 | 82.58 | 12.40 |
| 69 | 52.30 | 7.45 | 90.84 | 13.29 |
| LSD (0.05) | 11.04ns | 2.30ns | 14.24ns | 2.70ns |
| CV (%) | 20.79 | 30.57 | 15.48 | 19.52 |
| Control | 14.84 | 3.81 | 22.27 | 5.80 |

Where, SNU= straw nitrogen uptake, SPU= straw phosphorus uptake, TNU= total nitrogen uptake, TPU= total phosphorus uptake, LSD= Least Significant Difference at 5% level; CV= Coefficient of Variation, \*= Significant (5%), \*\*= Highly Significant (1%), NS= non -significant. At a 5% level of significance, there are no significant differences in means across columns and rows with the same letters.

### **Phosphorus uptake by grain and straw**

The ANOVA results indicated that grain P uptake was significantly affected (p < 0.05) by the interaction of N and P applications. The maximum grain P uptake (9.38 kg ha-1) was achieved with the combination of 184 kg N and 69 kg P2O5 ha-1, however, the minimum grain P uptake (1.99 kg ha-1) was observed in the control plots (Table 7). This finding indicates that higher N levels enhance P uptake in tef. This might be because higher nitrogen levels improve phosphorus uptake in tef by promoting root growth, increasing the plant’s demand for phosphorus, and enhancing its availability in the soil. This synergistic interaction highlights the need for balanced nutrient management to achieve optimal crop performance. Similarly, Fosu-Mensah and Mensah (2016) noted that applying N and P significantly enhanced P uptake in maize grains. Results showed that straw and total P uptake was highly significantly (p≤0.001) influenced by the main effects of varying N rates. The highest straw P uptake (8.52 kg ha-1) occurred in plots treated with 138 kg N ha-1, which was statistically comparable to the uptake in plots receiving 184 kg N ha-1. The lowest uptake (3.81 kg ha-1) was found in the control plots, suggesting that P uptake in straw increases with higher N fertilizer levels (Table 6). Results showed that the application of 184 kg N was given the highest (16.29 kg ha-1) total P uptake and the lowest (5.8 kg ha-1) was observed from the unfertilized plot (Table 6). This might be due to relatively higher straw yield and straw P uptake, which resulted in increased total P uptake by straw. The outcome indicated that total P uptake rises with increasing N rates, but there was no significant difference in P rates on total p uptake. This may be because the soil already contains sufficient phosphorus for tef growth, so additional phosphorus does not lead to significantly higher uptake since the plants' nutrient requirements are already satisfied. In agreement with this finding, Bereket *et al*., (2014) revealed that N fertilizer resulted in significantly greater total P absorption. Amare *et al*., (2013) reported that P uptake by wheat grain increased with higher N levels. In addition, fertilizing N with P significantly increased P absorption, suggesting that these nutrients were more accessible in the soil (Fosu-Mensah and Mensah, 2016). This implies that the application of N may enhance P uptake by plants.

Table 7; Interaction effects of grain N and P uptake as affected by N and P2O5 rates.

|  |  |  |  |
| --- | --- | --- | --- |
| N rates | P2O5 rates | GNU | GPU |
|  | 23 | 15.96d | 3.82d |
| 46 | 46 | 26.47cd | 5.45bcd |
|  | 69 | 30.18bc | 3.99cd |
|  | 23 | 32.18abc | 5.79bcd |
| 92 | 46 | 43.66a | 5.14bcd |
|  | 69 | 44.39a | 5.69bcd |
|  | 23 | 38.42abc | 6.25b |
| 138 | 46 | 34.41abc | 4.27bcd |
|  | 69 | 37.82abc | 4.31bcd |
|  | 23 | 40.53ab | 6.08c |
| 184 | 46 | 37.98abc | 8.69a |
|  | 69 | 41.78ab | 9.38a |
| LSD (0.05) |  | 12.66\* | 2.13\* |
| CV |  | 16.30 | 16.87 |
| Control |  | 7.42 | 1.99 |

Where, GNU=grain nitrogen uptake (kg ha-1), GPU= grain phosphorus uptake (kg ha-1), LSD= Least Significant Difference at a 5% level; CV= Coefficient of Variation, \*= Significant (5%), \*\*= Highly Significant (1%), NS= non -non-significant. At a 5% level of significance, there are no significant differences in means across columns and rows with the same letters.

## Correlation Analysis

The yield and their attributes of tef indicated a highly significant (p≤0.001) positive, negative, and linear relationship (Table 9). The results indicated a significant positive correlation between the grain yield of tef and the variables of plant height (r=0.692\*\*), panicle length (r=0.730\*\*), effective tillers per plant (r=0.820\*\*), biomass yield (0.82\*\*), and straw yield (r=0.541\*\*). This suggests that when plant height, panicle length, effective tillers per plant, biomass yield, and straw yield raise grain yield significantly increases. This is because the substantial increase in grain yield from enhanced vegetative growth, greater reproductive development, and more efficient use of nutrients and resources. Key traits such as plant height, panicle length, effective tillers, biomass yield, and straw yield are essential for optimizing the plant's grain production potential. In addition, days to 90% physiological maturity (r= -0.366\*\*) had a negative association with grain yield which was similar to the finding of Getahun *et a*l., (2018) on tef. Also, plant height, panicle length, biomass, grain yield, and straw yield had a positive and strong association with lodging percentage. Except for days to maturity, grain yield showed a strong and positive association with growth parameters. This suggested that applying combined N and P fertilizers improved the production and yield components, which in turn improved yield in the Dembia and Takusa districts. Similarly, plant height (r = 0.732\*\*) and panicle length (r=0.708\*\*) had a significant and positive relationship with straw yield. However, days to 90 % maturity (r= -0.395\*\*) had a negative relationship. This reveals that a rise in plant height and panicle length results in a significant increase in straw output. The current finding is in line with Getahun *et al*., (2018) and Bekalu and Arega (2016) findings who described that plant height and panicle length of tef had a strong positive association with grain and straw yield, however a negative relationship with maturity and heading. Likewise, Tewolde *et al*., (2020) revealed that greater straw yield is significantly influenced by both the maximum plant height and the abundance of tillers.

Table 8; Pearson correlation coefficients of the main characters of tef.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Traits | DTM | PH | PL | ETP | BM | GY | STY | HI | LI |
| DTM |  |  |  |  |  |  |  |  |  |
| PH | -.426\*\* |  |  |  |  |  |  |  |  |
| PL | -.305\*\* | .907\*\* |  |  |  |  |  |  |  |
| ETP | -.202ns | .667\*\* | .721\*\* |  |  |  |  |  |  |
| BM | -.417\*\* | .776\*\* | .761\*\* | .574\*\* |  |  |  |  |  |
| GY | -.366\*\* | .692\*\* | .730\*\* | .820\*\* | .660\*\* |  |  |  |  |

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| STY | -.395\*\* | .732\*\* | .708\*\* | .481\*\* | .989\*\* | .541\*\* |  |  |  |
| HI | .115ns | -.212ns | -.155ns | .172ns | -.539\*\* | .221ns | -.647\*\* |  |  |
| LI | -.284\* | .815\*\* | .741\*\* | .196 | .869\*\* | .438\*\* | .843\*\* | -.552\*\* |  |

DM = Days to 90% Physiological Maturity, PH = Plant Height, PL=panicle length, ETP=Effective tiller per plant, GY=Grain Yield, BM = Biomass Yield, STY=Straw yield, HI = Harvest Index (%),NS: Non-Significant, \* =significant difference at 5% & \*\*= highly significant difference at 1%.

## Partial Budget Analysis

The results of the partial budget analysis are listed in Table (9). The highest NB ETB 215219.76 ha-1 with an acceptable MRR of 1684.97 % was found with the combined application of 92 kg N ha-1 and 46 kg P2O5 ha-1. The second higher NB of ETB 188260.24 ha-1 with the highest MRR of 4874.41 % was found with the combined application of 92 kg N ha-1 and 23 kg P2O5 ha-1 fertilizer rate while the lowest NB of ETB 41156.91 on the control plot. According to a partial budget analysis, farmers will shift to adopt a recommended new agricultural technology only if they receive a minimum MRR of 100%, which translates to an increase in net return of at least 1 birr for every 1 birr invested (CIMMYT, 1988). Given that the highest NB of ETB 215219.76 ha-1 with an acceptable level of MRR (1684.97) was observed at 92 N and 46 kg P2O5 ha-1. Therefore, tef growers in the study areas (Takusa and Dembia districts) and other similar agroecologies and soil types are advised to apply 92 N and 46 kg P2O5 ha-1 which are cost-effective and economically feasible.

Table 3; Partial budget analysis of the effects of N and P2O5 rates on tef production

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| TRT | GY | AGY | STY | ASTY | TVC | GB | NB | DA | MRR |
| 0/0 | 411 | 369.9 | 1543.3 | 1388.97 | 0 | 41156.9 | 41156.9 |  |  |
| 46/23 | 890 | 801 | 3818.3 | 3436.47 | 3840 | 107592 | 103752 |  | 1630.07 |
| 46/46 | 1540 | 1386 | 3320 | 2988 | 5440 | 162504 | 157064 |  | 3332.02 |
| 92/23 | 1660 | 1494 | 6241.7 | 5617.53 | 6080 | 194340 | 188260 |  | 4874.41 |
| 46/69 | 1760 | 1584 | 3426.7 | 3084.03 | 7040 | 183072 | 17603.2 | D |  |
| 92/46 | 1970 | 1773 | 6333.3 | 5699.97 | 7680 | 222900 | 2152193 |  | **1684.97** |
| 138/23 | 1630 | 1467 | 6740 | 6066 | 8320 | 195228 | 186908 | D |  |
| 92/69 | 2010 | 1809 | 5816.7 | 5235.03 | 9280 | 222780 | 213500 | D |  |
| 138/46 | 1680 | 1512 | 7715 | 6943.5 | 9920 | 206748 | 196828 | D |  |
| 184/23 | 1510 | 1359 | 7468.3 | 6721.47 | 10560 | 189672 | 179112 | D |  |
| 138/69 | 1670 | 1503 | 6573.3 | 5915.97 | 11520 | 197628 | 186108 | D |  |
| 184/46 | 1440 | 1296 | 8206.7 | 7386.03 | 12160 | 188688 | 176528 | D |  |
| 184/69 | 1490 | 1341 | 8633.3 | 7769.97 | 13760 | 196260 | 182500 | D |  |

TRT= Treatment Combinations, GY=Grain Yield (kg ha-1), AGY= Adjusted Grain Yield (kg ha-1), STY=Straw Yield (kg ha-1), ASTY= Adjusted Straw Yield (kg ha-1), GB= Gross Benefit (ETB), DA=Dominance Analysis, TVC= Total Cost that Vary (ETB), NB= Net Benefit (ETB), MRR= Marginal Rate of Return (%), ETB=Ethiopian Birr.

# CONCLUSION

In the present study, the application of N and P nutrients significantly affected the yield and yield components of tef. Nitrogen (N) fertilizer had highly significant effects on most growth and yield components, including plant height, panicle length, biomass yield, and nutrient uptake. Phosphorus (P₂O₅) significantly affected biomass yield and plant height. The interaction of N and P fertilizers influenced effective tillers per plant, grain yield, harvest index, and grain N and P uptake. The highest grain yield (2.01 t ha-1) was observed with 92 kg N ha-1 and 69 kg P₂O₅ ha-1, and the highest biomass yield (9.75 t ha-1) with 184 kg N ha-1. The best economic return was achieved with 92 kg N ha-1 and 46 kg P₂O₅ ha-1. Thus, this combination is recommended for tef growers in Dembia and Takusa districts and other similar agroecologies in Northwestern Ethiopia.

**ACKNOWLEDGMENTS**

The experiment was conducted with financial support from the Amhara Regional Agricultural Research Institute (ARARI) and the Gondar Agricultural Research Center (GARC). We sincerely thank GARC for facilitating and funding the study. Additionally, we express our gratitude to the farmers for graciously allowing us to carry out the experiment on their farms.

**CONFLICT OF INTEREST**

There are no any conflicts of interest, the authors claim.

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