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Teff (*Eragrostis tef*) dry matter yield, nutrient uptake partitioning, and nitrogen use efficiency indices affected by nitrogen rate under balanced fertilization

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ABSTRACT

Teff [*Eragrostis tef* (Zucc.) Trotter] has gained high demand and popularity across the world in recent years. Data on nutrient uptake and partitioning and nitrogen use efficiency (NUE) indices of teff under balanced fertilization are scarce. A greenhouse experiment was conducted to study the effect of six different nitrogen (N) rates (0,25,50,100,150,200 mg N kg^{-1}) on the agronomic performance of teff. These treatments were arranged in a Complete Randomized Design with four replicates. Aboveground dry matter N and phosphorus (P) uptake increased with an increasing N rate, while potassium (K) uptake increased up to 50 mg N kg^{-1} and then started to decline. The dry matter yield followed the order straw > grain > roots. N uptake followed the order grain > straw > roots. P uptake also showed significant ($p < 0.001$) differences across the plant parts and followed the order grain > straw > roots. Most of the K was taken up by straw, followed by grain and roots. N fertilization had a significant ($p < 0.001$) effect on grain protein, N partial factor productivity and NUE of teff. Differences in N harvest index, N recovery efficiency, N agronomic efficiency, and N agrophysiological efficiency were not statistically significant due to the N rate. Nitrogen rates of 100 mg kg^{1} gave an optimal NUE for teff. However, the application of 150 mg kg^{1} N rate resulted in the highest grain yield. Additionally, the results indicated a negative correlation between yield and NUE. In summary, our findings suggest that applying 150 mg kg N^{-1} to teff could be considered a beneficial nitrogen fertilization practice. This approach enhances yield, nutrient uptake, and various traits related to nutrient use efficiency, thereby elevating teff's importance as both a food and feed crop.

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Introduction

Teff [*Eragrostis tef* (Zucc.) Trotter] is a panicle-bearing C4 tropical cereal that has its center of origin and diversity in the northern Ethiopian highlands (Demissie, 2011). Teff is an important food grain in Ethiopia, mainly used to make *injera*, a traditional soft, porous, thin fermented pancake with a sour flavor (Schneider & Anderson, 2010; Yigzaw et al., 2004). Teff is grown both for its grain and straw in Ethiopia. Teff's international popularity is rapidly growing (Provost & Jobson, 2014) because of its gluten-free nature (Hopman et al., 2008) and a rich source of protein and nutrients (Bultosa, 2007). Teff has an attractive nutritional profile; it is high in dietary fiber, thiamine, phosphorus (P), calcium (Ca), iron (Fe), and copper (Cu) and an excellent composition of amino acids essential for humans (Doris Piccinin, 2010).

Teff covers the largest area annually in Ethiopia at 23% of its arable land and ranked second in grain production (16.12%) in the 2019/20 cropping season. An area of 3.0 million hectares was cultivated and yielded 5.5 million metric tons (Central Statistics Agency of Ethiopia (CSA, 2021)). Teff yields are still among the lowest compared with other cereals such as wheat. Some of the factors that cause low productivity are lodging, method of planting and fertilizer application and the combined effect of these factors resulting up to 22% reduction in grain and straw yield (Gebretsadik et al., 2009). This decrease in yield is influenced by various factors including waterlogging, drought, and nutrient limitations (Tulema et al., 2005). Lodging, which occurs due to falling of shoots and root (van Delden et al., 2010) of teff is one of the factors reducing teff yield between 30% and 50% (Assefa et al., 2011). Besides the natural factors such as shallow root system and weak stem, unbalanced fertilization especially excess N cound contribute for lodging of teff (Girma et al., 2012; Wato, 2019). Teff has a yield

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potential of up to 4600 kg ha^{-1} by reducing the effect of lodging (Teklu & Tefera, 2005), which is one of the major yield limiting factor for teff. Hence, developing lodging resistance cultivars have been the major focus of teff breeding research for years (Assefa et al., 2011; Ketema, 1993; Tadele & Assefa, 2012; Tefera et al., 2001). Besides, different planting methods and management practices such as reducing seed rate, row planting and transplanting (Mihretie et al., 2021), balanced fertilization (Misskire et al., 2019; Mulugeta et al., 2020) were tested to reduce lodging of teff, which resulted a significant improvement. A report from Mihretie et al. (2021) indicated that planting methods influenced teff yield more than plant density.

Currently, Ethiopia produces over 90% of the world's teff. But because of its growing demand and popularity as palatable forage and high-quality food in various parts of the world, teff production has attracted other countries including Australia, China, India, South Africa, the USA, Netherlands and Germany, South Africa being the major exporter of teff for the European market. In Ethiopia, teff production is mainly rainfed, and there are varieties adapted to varying rainfall regimes. But teff can also be grown with irrigation especially for forage production, where multiple harvests are possible. Generally, irrigation with better nutrient management results higher yields as the crop will not be stressed, especially at its critical stages. For instance, Mengiste et al. (2011) showed that above ground biomass yield and grain yield can be maximized by applying optimum amount of water throughout the growing season. This may not be the case in rainfed agriculture, especially in areas where rainfall patterns are unpredictable. In a fertigation experiment conducted in a semiarid Mediterranean climate, Gashu et al. (2020) found that teff exhibited nitrogen deficiency at lower application rates and experienced yield penalties at higher rates due to over-fertilization that resulted in excessive vegetative growth at the expense of yield. Nitrogen (N) ranks as the second most critical factor influencing plant productivity, following water (Plett et al., 2020). It is an important mineral nutrient for producing cereal crops since high yields depend on an adequate N supply (Ladha et al., 2016). N is commonly taken up from the soil as ammonium (NH_4^+) or nitrate (NO_3^-) (Cui et al., 2017; Poothong & Reed, 2016). These different nitrogen form exert varying effects on plant physiological and metabolic processes, including nutrient uptake, enzyme activity, photosynthesis rate, respiration rate, water balance, and signaling pathways (Szczerba et al., 2008). Ultimately, these influences contribute to the overall growth and yield of plants and crops.

Agronomic nitrogen use efficiency (NUE) is a measure of the amount of N taken up by a crop compared to the amount applied. Since it shows the relationship between N inputs and crop yield, it is considered as an important indicator of environmental sustainability and economic efficiency in crop production (EU Nitrogen Expert Panel, 2015). NUE can be defined more broadly as the ratio of crop N uptake to the available soil N, which would include applied fertilizer N plus residual mineral N in the soil. The greater the ratio, the better the NUE (Davis, 2007). Plant NUE is a complex physiological trait that depends on relative N availability in the soil and photosynthetic carbon fixation to provide energy for N uptake and the precursors that are required for amino acid biosynthesis (Hirel et al., 2007). The overall efficiency of applied N is generally less than 50% in the tropics (Baligar & Bennett, 1986) and less than 70% in temperate regions (Malhi et al., 1992). One of the key factors considered in high-input agriculture, therefore, is the improvement of the NUE for sustainable and profitable N use (Ahrens et al., 2010).

Even though teff is a high-value crop, it received insefficient research attention, especially with regard to balanced fertilizer application. Currently, fertilizer application is based on blanket recommendation that has been in use for decades. As a result, grain yields remain low (<2 tons ha^{-1}), which is about half of its potential (Hailu & Seyfu, 2000). There are studies that examined the influence of N rate on yield and yield components (Ayalew et al., 2011; Tulema et al., 2005) and nutritional traits (Tietel et al., 2022) of teff; however, there are no known prior reports regarding the effects of N rate under balanced fertilization on nutrient uptake and partitioning of macronutrients in teff plant components. Understanding the latter will benefit future grain yield advancement from both practical and breeding perspectives. Accordingly, this trial was conducted to study the effects of different N rates under application of optimum levels of other nutrients and water on yield and yield components and concentration and uptake of nutrients in various parts of teff and to evaluate the NUE indices on teff. The findings from this study may be valuable in the development of an improved N management practice to optimize yield and NUE for sustainable teff production.

Materials and methods

A pot experiment was conducted between February and June 2020 at the IFDC greenhouse in Muscle Shoals, Alabama, situated at 34°46'09.46'N latitude and 87°39'16.04'W longitude at an altitude of 167 m above mean sea level. The daily mean temperature in the greenhouse ranged from 19 °C in March when seeds were sown to 27 °C at the end of June when the crop was harvested. Similarly, the daily mean relative humidity (RH%) in the greenhouse ranged from 69% in March to 74% in June. The soil used in the experiment was Sumter clay loam (fine-silty, carbonatic, thermic Rendollic Eutrudepts). The Sumter series consists of moderately deep, moderately well-, or well-drained, slowly permeable soils (https://soilseries.sc.egov.usda.gov/OSD_Docs/S/SUMTER.html). The soil had a pH of 8.2 and contained 0.23, 2.21, 0.24, and 0.93 mg kg^{-1} of DTPA Soluble Zn, Fe, Cu, and Mn, respectively. The ammonium acetate soluble Ca, K, Mg, and Na were 36.68, 0.26, 0.31, and 0.07 coml kg^{-1}, respectively. The MCP-S was 5.26 mg kg^{-1}. The iron hydroxide Pi—P was 8.27 mg kg^{-1}. Nutrients P, K, Mg, Zn, Cu, and Mn were low (deficient), S was medium, and Ca was high according to the categories of nutrient concentration in the soil defined by Marx & Hart Rgs (1999).

Pots with dimensions of 24 cm, 16 cm, and 20 cm for the top diameter, bottom diameter, and height, respectively, were used. The soil was prepared by removing non-soil materials, and 8 kg was used in each pot. Six rates of nitrogen − 0, 25, 50, 100, 150, and 200 mg kg^{-1} soil in the form of urea were applied in three splits (basal, tillering, and heading stages). To provide a non-limiting amount of nutrients based on the soil test, basal doses of 100, 150, 24, 2, 6, 3, 2, 0.5, and 0.05 mg kg^{-1} of P, K, Mg, Cu, Zn, Fe, Mn, boron (B), and molybdenum (Mo), respectively, were uniformly incorporated into the soil. Nutrient sources used were the muriate of potash (KCl) for K, mono calcium phosphate (MCP) for P, and complete solution containing Mg and micronutrients made from sulphates of Mg, Cu, Zn, Fe and Mn, and sodium tetraborate and sodium molybdate for B and Mo, respectively, The nutrient quantities are in elemental form. The N, P, and K fertilizers applied basally were granules, while the Mg and micronutrients and last two urea splits were applied as a solution. The experiment was laid out in a complete randomized design (CRD), with four replicates. Soil and these predetermined quantities of fertilizer were thoroughly mixed for 1 min in a 5-gallon (18.93 L) bucket using an electric drum mixer before transferring to the experimental pots. Prior to sowing, the soil pots were treated with a fungicide: 1 L Actinovate solution (2.8 g per gallon of water). A high-yielding and white-seeded teff variety, Quncho (DZ-Cr-387 RIL-355), was used as the test crop. Ten teff seeds were sown at about 1.5 cm depth on and thinned to grow to five teff plants per pot (which is equivalent to the 5–10 kg ha^{-1} seed rate (Kitata et al., 2020; Mengie et al., 2021; Mihretie et al., 2021) 2 weeks after emergence. Deionized water was applied using an automatic drip irrigation system, and pots were kept weed-free for the entire growing period.

Observations were recorded on growth and yield performance of the teff crop. On the 55th day after emergence, SPAD index (greenness of plants) was measured on three healthy top leaves using a SPAD 502 Chlorophyll meter (Konica Minolta Sensing Inc., Osaka, Japan). Plants were manually harvested from each pot, and plant parts were divided into straw, grain, and roots at maturity. At the time of harvest, plant height was measured from the soil surface (base of the main stem) to the top of the plant, and tiller number (total and fertile), excluding the main shoot, was counted and recorded. The panicle (the inflorescence of teff plant) length (cm) was measured starting from the node where the first panicle branch emerged to the tip of the panicle in each pot and its respective dry weight recorded. The roots were carefully extracted from the soil in a plastic tray. Initially, larger and more visible roots were handpicked, followed by a meticulous sieving process utilizing various sizes of sieves. After sieving, the roots underwent a thorough washing procedure, during which any floated roots were carefully collected. Subsequently, the roots were rinsed with distilled water to ensure purity before commencing the drying process. The plant samples were dried at 70°C to a constant weight. After drying, aboveground biomass was determined, and the plant samples were threshed and cleaned to determine grain yield, and straw yield. The dried samples were milled, and the root, straw and grain were analyzed for nutrient content using the following procedures. N was determined using a micro-Kjeldahl method, a modification of the aluminum block digestion technique described by Gallaher et al. (1975) P was analyzed using the molybdenum blue method (Murphy & Riley, 1962). K was analyzed using a Spectro Arcos ICP-OES analyzer (SPECTRO Analytical Instruments GmbH, Kleve, Germany). The quantities of nutrients in the plant tissues were expressed as milligrams of nutrient per kilogram of plant on a dry weight basis. Nutrient uptake was calculated as a product of nutrient concentration and dry weight of the respective plant parts and expressed as milligrams per pot.

The N-related physiological parameters and efficiencies were determined as per the following equations (Dobermann, 2005; Fageria et al., 2008):

Nitrogen Recovery Efficiency (NRE), (g N uptake g^{-1} N fertilizer × 100), %

$$NRE = (N_{fup} - N_{cup}) * 100/FN$$

Nitrogen Agronomic Efficiency (NAE), (g grain g^{-1} N fertilizer)

$$NAE = (GY_f - GY_c)/FN$$

Nitrogen Partial Factor Productivity (NPFP), g g^{-1}

$$NPFP = GY_f \, FN^{-1} \text{ (often called NUE)}$$

Agrophysiological Efficiency (APE, g g^{-1})

$$(GY_f - GY_c)/(N_{fup} - N_{cup},)$$

Nitrogen Harvest Index (NHI), %

$$NHI = (N_{upg} \, N_{fup}^{-1}) *100$$

N Uptake Efficiency (NUpE) g g^{-1}

$$N_{fup} \, FN^{-1}$$

N Utilization Efficiency (NUtE) g g^{-1}

$$GY_f \, N_{fup}^{-1}$$

Nitrogen Use Efficiency (NUE)

$$NUE = NUpE \times NUtE\text{; alternatively,}$$

$$NUE = GY_f \, FN^{-1} \text{ (kg grain kg}^{-1}\text{ N fertilizer)}$$

Crude Protein of Grain

Concentration of N (%) in the grain × 6.25

Where:

N_{fup} is N uptake (grain + straw) from fertilized pots and N_{cup} is N uptake (grain + straw) from control (0N) pots, both in g pot^{-1}.

GY_f is grain yield from fertilized pots, and GY_c is grain yield from control (0N) pots.

N_{upg} is N uptake by grain.

FN is total fertilizer N applied in g pot^{-1}.

For each variable, a one-way analysis of variance (ANOVA) was carried out to determine the effects of nitrogen rate on the parameters studied, using SAS package (Statistical Analysis Systems, Cary, NC, USA, 2021). Mean separations were computed using the least significant difference (LSD) test, and treatment differences were considered significant at 5% probability level.

Results

Yield and yield components and SPAD index

Total aboveground dry matter yield, straw, grain, and root biomass yields, fertile tiller per plant, harvest index and the SPAD index were significantly ($p < 0.001$) increased with increasing N rate (Table 1). On the other hand, plant height and panicle weight did not show any significant difference among N rates.

The three lower rates of N (0, 25, and 50 mg kg^{-1}) resulted in similar root dry matter yield, and a significant increase occurred above these rates. The 150 mg kg^{-1} N rate had the highest HI and was greener than the rest of the treatments. Total aboveground biomass, which is the sum of straw and grain continued to increase with an increasing N rate. Grain yield ranged from 27 to 57 g pot^{-1}, while the fertile tiller per plant was between 7 and 13 tillers, the highest being from the 200 mg kg^{-1} rate and the lowest from the control. Straw yield, grain yield and number of fertile tillers almost doubled at higher rate compared to the control pot (that receives same amount of all nutrients except N) showing the importance of N for teff.

Dry matter and nutrient uptake partitioning

Dry matter and nutrient uptake partitioning were evaluated for both root and aboveground (straw and grain) parts. Taking the sum of root, straw, and grain as the total, dry matter yield was in the order straw > grain > roots, with a root weight of 3–5%, straw yield of 63–69%, and grain yield of 27–32% of the total yield depending on the N rate (Table 1). As nutrient uptake is the product of nutrient content and yield, in this experiment the N, P, and K uptake in root, straw and grain were significantly ($p < 0.001$) affected by the N application rate. Higher uptake of these nutrients was observed at higher rates of N (150 and 200 mg kg^{-1}) (Table 2). The uptake of N, P and K by straw also showed a significant effect. Straw N uptake increased with an increasing N rate, while P uptake decreased with an increasing N rate. Straw K uptake was highest at 50 mg kg^{-1} K rate and decreased afterwards. On the other hand, N, P and K uptakes by grain were significantly ($p < 0.001$) affected by N rate, showing an increase with increasing N rate. The increase in N uptake was linear, while P and K uptake showed a nonlinear pattern. Uptake of

Table 1. Effect of N rate yield and yield components and SPAD index on teff. Data shown are means from four replications

N Rate (mg kg^{-1})	RW (g pot^{-1})	SW (g pot^{-1})	GW (g pot^{-1})	AGBM (g pot^{-1})	Fertile tiller $plant^{-1}$	Total tillers $plant^{-1}$	Plant height (cm)	Panicle weight (g pot^{-1})	HI (%)	SPAD Index
0	3.4 ± 1.2^{b}	67 ± 4.0^{d}	27 ± 1.9^{d}	95 ± 4.6^{d}	6.7 ± 0.5^{d}	7.5 ± 0.1	143 ± 5.3	6.4 ± 0.5	29 ± 1.7^{bc}	32 ± 2.2^{d}
25	3.6 ± 1.1^{b}	77 ± 7.7^{d}	31 ± 5.9^{d}	107 ± 13.4^{d}	7.3 ± 0.9^{d}	8.0 ± 0.7^{d}	150 ± 10.5	6.6 ± 0.5	28 ± 2.1^{c}	33 ± 0.7^{cd}
50	3.9 ± 0.3^{b}	92 ± 3.7^{c}	39 ± 5.2^{c}	131 ± 8.4^{c}	9.6 ± 1.8^{c}	10.7 ± 1.8^{c}	144 ± 9.9	6.6 ± 1.5	30 ± 2.2^{bc}	35 ± 1.8^{bc}
100	6.7 ± 2.1^{a}	107 ± 5.6^{b}	49 ± 2.6^{b}	156 ± 6.9^{b}	10.9 ± 1.7^{bc}	12.0 ± 1.6^{bc}	150 ± 6.8	7.3 ± 0.9	31 ± 1.4^{ab}	36 ± 1.4^{abc}
150	8.7 ± 2.4^{a}	115 ± 7.1^{b}	57 ± 4.04^{a}	171 ± 7.9^{a}	12.1 ± 1.0^{ab}	13.3 ± 1.1^{ab}	142.9 ± 2.7	7.4 ± 0.7	33 ± 2.2^{a}	38.4 ± 2.6^{a}
200	9.3 ± 2.8^{a}	127 ± 8.3^{a}	56 ± 6.3^{a}	183 ± 13.3^{a}	12.8 ± 0.9^{a}	14.5 ± 0.7^{a}	144.1 ± 2.8	7.2 ± 1.3	31 ± 1.8^{abc}	38.1 ± 2.1^{ab}
p values	***	***	***	***	***	***	Ns	Ns	*	***

RW: Root weight; **SW**: Straw weight; **GW**: Grain weight; **AGBM**: Aboveground biomass; **HI**: Harvest index. Treatment means ± standard deviations within each column and treatment with different letters are significantly different at $p < 0.05$. Ns, not significant. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Table 2. Effect of N rate and growth stage on root dry matter and nutrient uptake. Data shown are means from four replications

N Rate (mg kg^{-1})	Root N Uptake (mg pot^{-1})	Root P Uptake (mg pot^{-1})	Root K Uptake (mg pot^{-1})	Straw N Uptake (mg pot^{-1})	Straw P Uptake (mg pot^{-1})	Straw K Uptake (mg pot^{-1})	Grain N Uptake (mg pot^{-1})	Grain P Uptake (mg pot^{-1})	Grain K Uptake (mg pot^{-1})
0	16.9 ± 6.4^{c}	2.2 ± 1.1^{b}	6.4 ± 4.2^{ab}	146.6 ± 21.4^{e}	63.4 ± 9.4^{a}	837.9 ± 56.3^{b}	278.6 ± 33.2^{d}	115.6 ± 7.7^{c}	165.8 ± 8.0^{b}
25	18.1 ± 5.3^{c}	1.9 ± 0.7^{b}	4.3 ± 2.6^{b}	181.1 ± 15.9^{ed}	70.9 ± 18.4^{a}	894.6 ± 34.5^{b}	340.9 ± 38.6^{d}	125.8 ± 18.8^{bc}	195.3 ± 25.3^{b}
50	20.6 ± 2.5^{bc}	1.9 ± 0.5^{b}	3.7 ± 1.4^{b}	213.4 ± 21.8^{d}	53.0 ± 22.7^{ab}	1680.1 ± 1145.6^{a}	470.5 ± 88.7^{c}	147.1 ± 8.2^{ab}	294.2 ± 73.4^{a}
100	38.0 ± 12.4^{b}	2.9 ± 1.1^{b}	5.8 ± 2.7^{b}	287.3 ± 35.4^{c}	39.2 ± 6.1^{bc}	1001.8 ± 58.5^{ab}	676.5 ± 89.9^{b}	157.6 ± 13.2^{a}	281.6 ± 21.3^{a}
150	58.9 ± 19.4^{a}	4.9 ± 1.8^{a}	11.9 ± 6.5^{a}	379.1 ± 16.8^{b}	28.6 ± 3.0^{c}	996.1 ± 39.0^{ab}	915.4 ± 50.2^{a}	155.8 ± 14.2^{a}	282.7 ± 26.0^{a}
200	70.7 ± 17.3^{a}	5.9 ± 1.4^{a}	9.1 ± 4.0^{ab}	542.8 ± 83.5^{a}	41.1 ± 5.1^{bc}	1188.6 ± 360.4^{ab}	952.4 ± 86.0^{a}	154.4 ± 21.9^{a}	293.4 ± 30.0^{a}
p values	***	***	Ns	***	**	Ns	***	**	***

Treatment means ± standard deviations within each column and treatment with different letters are significantly different at $p < 0.05$. Ns, not significant. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

these nutrients was in the order *N* > K >P in root and grain, while it was in the order K > *N* > P in straws of teff. Uptake of N ranges from 17–71 mg pot^{-1} in roots, 147–543 mg pot^{-1} in straw and 279–952 mg pot^{-1}. Root P uptake also ranged from 2–6 mg pot^{-1} in roots, 27–71 mg pot^{-1} in straw and 116–158 mg pot^{-1} in grain. Similarly, K uptake was in the range from 4–12 mg pot^{-1} in roots, 838–1680 mg pot^{-1} in straw and 166–294 mg pot^{-1} in grains.

N uptake ranged from 3% to 5% in roots, 28% to 35% in straw, and 60% to 68% in grain and increased with an increasing N rate in all the three plant parts. The P uptake was also significantly different across the plant parts, ranging from 1% to 3% in roots, 15% to 36% in straw, and 63% to 82% in grain. P uptake decreased with an increasing N rate in straw but increased with an increasing N rate in both roots and grain. However, most of the K uptake was by straw, followed by grain. K uptake ranged from 0.2% to 0.9% in roots, 77% to 83% in straw, and 15% to 22% in grain.

Nitrogen use efficiencies indices and protein content

The results indicate that N fertilization at various rates had a significant ($p < 0.001$) effect on NPFP, NUpE, NUE, NHI, NutE, and grain protein content of teff (Table 3). On the other hand, NRE, NAE and NAPE were not significantly affected by N rate on teff. NHI, NRE and protein content increased with an increasing N rate, while NAE, NPFP, and NUE decreased with increasing N rate. Protein content increased with an increasing N rate until the 150 mg kg^{-1} N rate; the increase between the 150 and 200 mg kg^{-1} rates was not significant.

The N rate significantly ($p < 0.001$) affected NPFP, NUpE, and NUE, resulting in a decrease in these parameters with an increasing N rate. On the other hand, the differences in NRE, NAE, and NAPE at each N rate were not statistically significant; NAE and NAPE were highest at 50 mg kg^{-1} N and then began to decline. The values of these parameters were in the following ranges: NRE 57–72%, NAE 18–29 g g^{-1}, NPFP 35–159 g g^{-1}, NAPE 27–45 g g^{-1}, NUpE 0.9–2.7 g g^{-1}, and NUE 35–159 g g^{-1} (Table 3). NRE showed an increasing trend until the 150 mg kg^{-1} N rate and then declined. The values were within the established range (50–80%) for a well-managed system (Fageria et al., 2011; Wortmann et al., 2007). NAE was highest at the 50 mg kg^{-1} N rate and then began to decline; the lowest NAE was with the 200 mg kg^{-1} N rate, although this was not significantly different from the other rates. The NPFP was significantly ($p < 0.001$) affected by N rate. It declined significantly with an increasing N rate, with a value of 159 g g^{-1} at 25 mg kg^{1} N and a value of 35 g g^{-1} at the highest rate of 200 mg kg^{-1} N. NAPE was highest at 50 mg kg^{-1} N and then decreased. There was

Table 3. Effect of nitrogen (N) rate on NUE indices and grain protein content. Data shown are means from four replications

N Rate	NAE	NPFP	NAPE	NUpE	NUE	NUtE (g g-1)	NRE (%)	NHI	Grain Protein
(mg kg^{-1})		——————————(g g-1)—————————-					————(%)————-		
0						63.8 ± 6.3^{a}		65.5 ± 3.9	6.5 ± 0.7^{d}
25	24 ± 22.6	159 ± 20.0^{a}	40 ± 23.6	2.7 ± 0.1^{a}	159 ± 20.0^{a}	59 ± 5.4^{ab}	57 ± 30.1	66 ± 3.2	7.0 ± 0.7^{cd}
50	29 ± 14.2	97 ± 12.9^{b}	45 ± 9.0	1.7 ± 0.2^{b}	97 ± 12.9^{b}	56 ± 1.5^{bc}	65 ± 26.9	68 ± 5.4	8.0 ± 0.6^{c}
100	27 ± 3.2	61 ± 3.3^{c}	41 ± 3.7	1.2 ± 0.2^{c}	61 ± 3.3^{c}	519 ± 4.0^{c}	67 ± 11.1	70 ± 0.6	9.0 ± 0.7^{b}
150	25 ± 3.9	47 ± 3.4^{cd}	34 ± 2.5	1.10.04 ± ^{cd}	47 ± 3.4^{cd}	44 ± 2.0^{d}	72 ± 6.4	71 ± 1.8	10.0 ± 0.3^{a}
200	18 ± 5.0	35 ± 3.9^{d}	27 ± 5.9	0.9 ± 0.1^{d}	35 ± 3.9^{d}	37 ± 3.5^{e}	67 ± 5.9	64 ± 4.5	11.0 ± 0.5^{a}
p values	Ns	***	Ns	***	***	***	Ns	Ns	***

Treatment means + standard deviations within each column and treatment with different letters are significantly different at $p < 0.05$. Ns, not significant. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.**NRE**: Nitrogen recovery efficiency; **NAE**: Nitrogen agronomic Efficiency; **NPFP**: Nitrogen partial factor productivity; **NAPE**: Nitrogen agrophysiological efficiency, **NUpE**: Nitrogen uptake efficiency; NUE: Nitrogen use efficiency; **NHI**: Nitrogen harvest index; **NUtE**: Nitrogen utilization efficiency.

no statistically significant ($p = 0.2817$) difference between the N rates. NUpE was significantly ($p < 0.001$) affected by N rate and declined with an increasing N rate, with values ranging from 1.1 g g^{-1} to 2.7 g g^{-1}. NUE was significantly ($p < 0.001$) affected by the N rate, with a decline as the N rate increased, ranging from 159 g g^{-1} to 35 g g^{-1}.

Discussion

The aims of this study were to evaluate the effect different levels of nitrogen on yield, nutrient uptake and partitioning and NUE indices and the relationship of these parameters under optimum application of other limiting nutrients and water. Results indicate that most of the parameters studied are significantly affected by N rate. The higher dry weight of N-treated plants could be attributed to the positive effect of N on the important constituents of nucleotides, proteins, chlorophyll, and enzymes and on various metabolic processes directly impacting the vegetative and reproductive phases of plants. N deficiency limits the productivity of crops more than any other element. Previous research has demonstrated greater yields and components of yields with increases in N application on sorghum (Kaizzi et al., 2012; Wortmann et al., 2007), maize (Arnall et al., 2013), wheat (Mullen et al., 2003) beans (Dianatmanesh et al., 2022), rice (Wang et al., 2017), Chinese rye grass (Chen et al., 2013) and teff (Alemayehu et al., 2023; Gashu et al., 2020; Tietel et al., 2022).

Previous research indicated that increased total biomass yield has a strong association with an increase in grain yield in cereals such as maize (Lorenz et al., 2010) and wheat (Bogale & Tesfaye, 2016). This potential for biomass accumulation has also been reported to be the driving force for mineral nutrient uptake and assimilation (Hanway, 1962; Karlen & Whitney, 1980). N uptake potential and grain yield are influenced by aboveground biomass production (Y. Peng et al., 2010). Moreover, grain yield improvements are associated with an increased harvest index (Duvick, 2005; Echarte & Andrade, 2003). Results obtained in the present study (Table 1) are in line with these reports. Similar results were also reported by Shah et al. (2015), who found that N and P uptake of wheat grain was higher than that of straw with an increasing N rate, while the K uptake of straw was higher than that of grain. In our experiment, the grain P uptake increased with N application (Table 2) showing that applied P was underutilized at lower N rates, the optimum uptake being at 100–150 mg N kg^{-1}, and decreased afterwards which might be due to dilution effect (Schlegel & Havlin, 2017).

NutE is the ratio between grams of grain per total N in aboveground dry matter of a mature plant. The NUtE addresses the yield produced per unit of N acquired by the plant shoots. The results of our study show that NUtE decreased with an increasing N rate (Table 3), indicating that the control plots were nutrient deficient, whereas inefficient internal nutrient conversion occurred at higher rates, which could have been caused by high N stress (Liu et al., 2011). These results are consistent with previous reports of a decrease in NUtE with an increasing N rate (Haile et al., 2012; Litke et al., 2019).

NHI is a measure of N partitioning in the crop, which provides an indication of how efficiently the plant utilized the acquired N for grain production (Dobermann, 2005; Fageria, 2014) and grain protein yield (Hirel et al., 2007). In this study, NHI increased with an N rate of up to 150 mg kg^{-1} N and then started to decline (Table 3). However, the difference between the rates was not statistically significant ($p = 0.0876$). These results are consistent with those of (Liang et al., 2014), who reported a quadratic relationship between N rate and NHI, indicating low efficiency in utilizing acquired N for grain N production at the highest N fertilizer rates. Similarly, grain protein content of teff increased with increased N rate in this experiment (Table 3), which is in line with previous studies that showed increased protein content of the grain of wheat (Gauer et al., 1992; Haile et al., 2012), maize (Hammad et al., 2022) and rice (Liang et al., 2021).

NRE refers to the increase in crop uptake of nutrients in the above ground parts of the plant because of its application. The increase in NRE with increasing N rate in this experiment (Table 3) which might be an indication that teff has the capacity to acquire N in response to the N input (Congreves et al., 2021). Similar results were reported by (Belete et al., 2018; Liang et al., 2014) on wheat. However, the results disagree with those of (Kassie & Fanataye, 2019), who reported a decrease in NRE with an increasing N rate on barley. Lower NRE levels suggest changes in management could improve efficiency or that nutrients are accumulating in the soil (Fixen et al., 2015). NAE indicates the ability of the plant to increase yield in response to the applied N (Craswell & Godwin, 1984). A higher NAE is an indication that the yield increment per unit of N applied is higher due to increased uptake and/or reduced losses of N (Craswell & Godwin, 1984). The common range of NAE values is 10–30 g g^{-1}; values higher than 30 indicate efficiently managed systems (Dobermann, 2005). Accordingly, the NAE values in this experiment fall within this common range (Table 3). These results align with reports by other researchers (Dhakal et al., 2021).

Table 4. Pearson correlation coefficients for physiology, yield and yield components, composition of teff and nutrient use efficiency indices across nitrogen fertilizer treatments

	SPAD	SW	GW	HI	RW	FTPP	RNU	SNU	GNU	NHI	NUtE	NUpE	NUE	Protein
SPAD	1													
SW	0.78	1												
GW	0.80	0.94	1											
HI	0.57	0.53	0.78	1										
RW	0.69	0.80	0.74	0.38	1									
FTPP	0.67	0.88	0.87	0.57	0.73	1								
RNU	0.69	0.82	0.77	0.41	0.98	0.77	1							
SNU	0.69	0.89	0.81	0.40	0.82	0.81	0.89	1						
GNU	0.81	0.94	0.97	0.69	0.79	0.89	0.84	0.89	1					
NHI	0.30	0.11	0.30	0.56	−0.04	0.19	−0.10	−0.22	0.21	1				
NUtE	−0.69	−0.86	−0.78	−0.34	−0.81	−0.82	−0.85	−0.93	−0.89	0.07	1			
NUpE	0.04	−0.06	−0.1	−0.1	−0.2	−0.09	−0.2	−0.15	−0.13	0.13	0.07	1		
NUE	−0.08	−0.19	−0.20	−0.15	−0.31	−0.22	−0.33	−0.29	−0.27	0.13	0.23	0.98	1	
Protein	0.77	0.88	0.85	0.50	0.80	0.87	0.84	0.90	0.94	0.14	−0.97	−0.09	−0.25	1

SW: straw weight**; GW**: grain weight; **HI**: harvest index; **RW**: root weight**; FTPP**: Fertile tillers per plant; **RNU**: root N uptake; **SNU**: straw N uptake; **GNU**: grain N uptake.

PFP is a useful measure of nutrient use efficiency as it provides an integrative index that quantifies total economic output relative to the utilization of all nutrient resources in the system (Singh et al., 2015). The 50 mg kg^{-1} rate was found to be a better rate compared to other rates in this experiment (Table 3). Lower values suggest overapplication of nutrients, while higher values suggest that the nutrient supply is likely limiting productivity (Fixen et al., 2015). Similar results have been reported in previous studies (Dhakal et al., 2021; Rawal et al., 2022). NUE is defined as the ratio of crop N uptake to the total input of N fertilizer. NUE can also be obtained as a product of two interacting components—NUpE and NUtE—which, respectively, accounts for the quantity of N extracted from the soil and the quantity of N translocated to grain and used for grain production (Moll et al., 1982). The decrease in NUE with an increasing N rate in this experiment (Table 3) indicated that the crops were able to take up more of the applied N at lower rates than the higher rates and that the applied N will have a positive impact on both the environment and farmers' profits. Previous studies showed a decrease in NUE with an increasing N application rate (Barbieri et al., 2008), indicating that NUE is greater when the yield response to N is high.

The yield components of teff are strongly correlated with yield (Table 4) and nutrient uptake. In this report, yield was negatively and highly correlated with NUtE showing the relatively lower ability of the cultivars to assimilate N in tissues and later translocate it to the grain to produce high yields. Previous results also indicated a weaker association between the rate of increases in yield with similar rate of increases in N uptake at crop maturity, resulting in a decline in NUtE (Gastal et al., 2015). On the other hand, NUE was highly correlated with NUpE than NUtE, showing more importance of NUpE than NUtE in this experiment, which was in line with previous reports (Ranjan et al., 2019). Contrary to this, other study reported that NutE was the predominant component contributing to NUE under high nitrogen, while NupE was more important than NutE for NUE under low nitrogen conditions (Peng et al., 2022).

Conclusion

This study demonstrates the potential impact of N application on yield parameters, nutrient concentration, and nutrient uptake of different parts of the teff crop under greenhouse conditions. The results show that nutrient concentrations, teff biomass yield and nutrient uptake were affected by N rate. Concerning the uptake partitioning, most of the N and P were taken up by grain, while K was taken up by straw. The application of N at higher rates (150–200 mg kg^{-1}) increased the N content in the grain, thus improving the protein content of the grain. In addition to improving the N and P content of grain, higher straw K concentration due to N application could be a potential benefit for farmers, as teff straw is a palatable feed for livestock. These are quality components that make teff a viable alternative both for human and animal nutrition. Nitrogen use efficiency indices were influenced by nitrogen rates. Grain and straw yields positively correlated with most of the parameters tested except the use of efficiency-related parameter. Overall, the application of 150 mg kg^{-1} N rate is recommended as it resulted in better grain yield of teff under this experiment. Future research is required to determine whether these benefits vary across cultivars. Further investigation of the effect of N rate and harvesting stage on the uptake of secondary and micronutrients under balanced nutrition is recommended.

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Author contributions

Conceptualization and Methodology, M.D., and U.S.; Conducting the Experiment, Plant and Soil Analysis, Data Collection, M.D., J.F.; Data Analysis, Writing Original Draft, Review and Editing, M.D.; Supervision and Technical Support, Review, Revising, and Editing, U.S., L.N., Z.S.; Project Administration and Funding Acquisition, U.S. and L.N. All authors have read and agreed to the final version of the manuscript.

Data availability statement

All the data used and/or analyzed during the study are available from the corresponding author upon reasonable request.

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