# 8. Response of Tef (*Eragrostis Tef (Zucc.) Trotter)*) to Nutrient Types under Rainy and Irrigation Production Systems in Highlands of Ethiopia

Zerfu Bazie[1*], Tadele Amare[1], Erkihun Alemu[1], Bitewulign Kerebh[1], Abere Tenagn[1], Abrham Awoke[1], Zmie Ambaw[1], Beamlaku Alemayehu[1], Anteneh Abewa[1], Ataklte Abebe[1], Tesfaye Feyisa[2], and Birhanu Agumas[2]

[1]Adet Agricultural Research Center, [2]Amhara Agricultural Research Institute (ARARI).

*Correspondence: zerfu24@hotmail.com

## Abstract

*Crops respond differently to nutrient types as a result of variations in the environment, soil, and management. The main problem with Ethiopian agricultural crop production is the poor selection of the necessary fertilizers for usage as an input. The objective of this study was to determine the most important nutrients to tef productivity on Vertisols and Nitisols. The experiments were conducted in three districts for the rainfed season, and one district irrigation season in the Amhara region, Ethiopia. Quncho and Gibie tef varieties were used as test crops for rainfed and irrigation seasons, respectively. Ten treatments composed of no fertilizer, All (NPKSZnB), All-B, All-Zn, All-S, All-K, All-P, All-N, RNP, and RNPS as well as RNP+S1 which have 30 Kgha$^{-1}$ S were applied. Three replications with a completely randomized block design were used to set up the experiment. Biological data were collected from a net plot area and analyzed using R version 4.1.1. When significant treatment means were found, mean separation using the least significant*

*the mean available P contents in vertisols and nitisols were 5.1 and 8.9 mgKg$^{-1}$, respectively, which is a low range. Whereas under the irrigation system, nitisols were found with 21.4 mgKg$^{-1}$ of soil P. The soil Nitrogen contents were found about 0.12% for nitisols and 0.15% for vertisols under rain fed season as well as 0.14% for nitisols under irrigation which was medium.*

*nutrient types compared to the negative control (without fertilizer application) and All-N treatments during the rainy and irrigation season.*

*0.01) varied to omitted nutrient types compared to l without fertilizer application and All-N treatments. However, there was no significant ($p < 0.05$) decline in yield due to the omission of Potassium, Sulphur, Zinc, or Boron. The lowest grain yields, 342 Kgha$^{-1}$ for vertisols and 491 Kgha$^{-1}$ for nitisols, were obtained when no fertilizer treatment was used. Application of K, S, Zn, and B did nothave any effect on tef yield compared to the applied NP nutrients. For vertisols and nitisols, N omission resulted in a 65 and 49% decrease in grain production. During the irrigation season, a yield decline of about 19% was also observed when N was omitted. As conclusion, P is only a limiting nutrient during the rain-fed season, but N is the nutrient that limits the yield of tef in both production seasons. To boost tef productivity, Ethiopian agriculture has to import the proper quantity of NP fertilizers with site-specific recommendations. It is suggested that the KSZnB nutrients in the farming system be periodically monitored.*

**Keywords*:*** Fertilizer, Limiting, Nutrient, Omission, Soil, Tef, Yield.

## Introduction

Maintaining soil resources while meeting the food demand of a high population is an unsolved problem (FAO, 2017). Chemical fertilizer played a major role in global food production over the past 60 years to feed the ever-increasing population. The current challenge for the Ethiopian agriculture sector is low productivity due to a high level of nutrient mining, low use of external inputs, traditional farm management practices, and limited capacity to respond to environmental shocks (Menna *et al.*, 2015; Desalegn *et al*., 2017; Agegnehu *et al*., 2015). The cropping area is subject to severe losses of nutrients due to soil erosion and the removal of dung and crop residue for fuel (Hurni, 1993). Nutrient balance studies by Stoorvogel and Smaling (1990) show that Ethiopia is among the countries with the highest rates of net nutrient losses. The annual nutrient deficit is estimated at -41 Kg N, -6 Kg P, and -26 $Kgha^{-1}$ K (Van Beek *et al*., 2016; Haileslassie *et al.,* 2005). Moreover, the nutrient balances in tef cropping systems are negative (–28 $Kgha^{-1}$ N) (Haileslassie *et al.,* 2006).

The maintenance of soil health depends on balanced fertilization, which includes the application of all the required plant nutrients in proper amount and form (Rakshit *et al*., 2017). Therefore, site-specific nutrient management involving along with spatial and temporal soil variability, crop requirements of nutrients, and cropping systems as well as without deteriorating soil and environmental quality is the most ideal system that needs to be practiced to achieve the targeted goals (Tiwari, 2007; Meena *et al.,* 2015; Sarkar *et al.,* 2017; Verma *et al.,* 2015). This situation leads to the use of correct fertilization which helps to boost the resilience of crops and therefore plays an important role in climate change adaptation. Though higher output and productivity are achieved by the application of more and different chemical fertilizers into the farmland (Rakshit *et al*., 2017) the application of selected nutrient types to the crop is vital. Because, crop plants are only able to convert about 33 % of the applied Nitrogen fertilizer (Ram and Johnson, 1999) and 10 – 15% of P (Roberts, and Johnston, 2015) to useful food products (grain).

Tef is a tropical grain that originated in Ethiopia and has a large diversity. It is thought to have been domesticated there and is recognized as a resilient crop (Ketema, 1997; Assefa *et al*., 2011). Because ithas grown under different environmental stresses in many parts of Ethiopia. Tef is also a $C_4$ annual small grain crop native to Ethiopia (Halpern *et al.*, 2021). It is also a gluten and glutenlike protein-free stable food crop (Spaenij-Dekking *et al.,* 2005; Baye, 2014). Tef grains are used as a daily protein source by two-thirds of the population in Ethiopia (Ereful *et al.,* 2022). It is cultivated on about two million hectares of land covering about 30% of the area under cereals.

Many efforts have been delivered to improve the productivity of tef in the rainy season although it still needs continuous work. Accordingly, many improved varieties and management options are included in tef production package. Nevertheless, less emphasis has been given to its production under irrigation and hence there is a technology package for tef under irrigation. The Amhara region is well known for its richness of water resources for irrigation. There is a successful start of tef production by irrigation in the Fogera and Mecha districts and the surrounding areas. Preliminary observations show that tef needs fewer amounts of water and labor compared to other horticultural crops. Therefore, this research proposal is designed to generate roles of different nutrient types under irrigation water management to enhance the productivity of tef and effectively use the existing water and market potential.

Fertilizer application has significantly increased the yields of crops (Belachew *et al.*, 2022). About 70 to 80 % of the inorganic fertilizer purchased by the smallholders is known to be applied to tef (Yirga and Hassan, 2013). Though fertilizer use in Ethiopia has increased notably since 1990, there is no concomitant yield increase (Zelleke *et al.,* 2010), especially in tef. Tef yield has been limited by low soil fertility and soil acidity (Agegnehu *et al.,* 2019), inappropriate use of fertilizer, low fertilizer use efficiency (Tarekegne and Tanner, 2001; Yirga *et al.,* 2002), inappropriate tillage, and climate variability (Habtegebrial *et al.,* 2007). Tef production is labor-intensive with low productivity (an average of 1.5 $tha^{-1}$ nationally) (Fissehaye *et al.,* 2009). Despite the potential for increasing yields of tef and farm income by the use of fertilizer, many small-scale and poor farmers do nothave the resources to make use of fertilizer for various reasons.

Commonly, Nitrogen and Phosphorus fertilizers have been applied in tef production for many years (Bekele, 2017). Previous blanket fertilizer recommendations are commonly used across different environmental conditions. These have not considered agro-ecological differences and soil variability (Shewangizaw *et al.,* 2021; Sileshi *et al.*, 2022; Dargie *et al*., 2022). Despite substantial increases in fertilizer use in the country (Zelleke *et al.,* 2010), deficiencies of N and P, K S, B, and Zn are reported in most of the Ethiopian soils (Beyene, 1983; Hailu *et al.*, 2015; EthioSIS, 2016) as well as Cu, Mn, and Fe are also deficient in some soils of sub-Saharan Africa (Kihara *et al.*, 2020). The higher use of mineral fertilizers is considered to be an essential option to close yield gaps (IFDC, 2015; Pradhan *et al.*, 2015; Chamberlin *et al.*, 2021), but profits cannot be maximized and sustained by applying unbalanced fertilizer applications over many years. Several fertilizer experiments on different crop types have been conducted over the last five decades and thus the empirical evidence confirmed that NP are deficient nutrients that must be supplied to crops in Ethiopia (Tanner and Hulluka, 1991; IFPRI, 2010; Amare *et al.*, 2018;2019; Bekele *et al.,* 2022). However, some researchers recently argued that KSZnB nutrients are also deficient and thus other nutrients are deficient with concrete evidence.

Currently, N, P, S, Zn, and B-containing fertilizers are imported and distributed in Ethiopia by the ministry of agriculture. To shift national fertilizer, and import policy, identifying and confirming the right fertilizer sources is mandatory in the farming system. Nowadays, developing a site and crop-specific nutrient recommendation for different agroecology and soil types as well as socioeconomic variabilities of farmers is a prerequisite agenda for sustainable crop production and profit in Ethiopian agriculture (Dargie *et al.*, 2022; Sileshi *et al.*, 2022). Selecting the right fertilizer types and balanced application of nutrients at appropriate rates to the local climate and every soil type is important to maximize tef yield (Johnston and Bruulsema, 2014). Though tef yield response to different soil nutrient types has been studied in some parts of Ethiopia, it is not well addressed in different soil types and locations in Northwestern Ethiopia. Despite, the recent expansion of tef with an irrigation system in the Amhara region, there are no research recommendations on nutrient management to enhance the productivity and profitability of tef production with irrigation systems. The purpose of this study is to elucidate the response of tef to different applied soil nutrients in nitisols and vertisols under rainy and irrigation production seasons in North West Ethiopia.

## Materials and Methods

*Study Site:* Nutrient omission experiments were conducted on multi- locations across farmers' fields on vertisols and nitisols in North Western Ethiopia. This experiment was conducted at 12 sites across three districts. The study was conducted across sites in farmlands of smallholder farmers in the Amhara region, Ethiopia (Figure 1). A similar nutrient omission trial was implemented during the irrigation production systems at two farmers' fields in the Mecha district which have the Koga irrigation scheme. The locations include; Yilmana Densa, Gonji Kollela, and Hulet Ejunebse districts. Yilmana Densa, Gonji Kollela, and Hulet Ejunebse are found about 42, 74.5, and 119 km from Bahir Dar on the way to Addis Ababa through Bichena, respectively. Mecha district is located *30 km south of Bahir Dar* on the way to Addis Ababa through Fnote Selam town. Three locations represent the major tef growing areas of west and east Gojjam Ethiopian highlands. Both vertisols and nitisols are the major soil types in the study sites. The experiment was conducted on nitisols in all districts whereas it was conducted on vertisols in both Yilmana Densa and Gonji Kolela districts during the rainy production season. Cereal-based cropping system is the dominant type of farming system in the study areas. The experimental sites received a uni-modal type of rainfall which extending from June to Augst in higher amounts. Maize, Tef, and Finger millet are the dominant cereal crops grown in the study areas. Bread wheat is also a dominant crop grown in Hulet Ejunebse district.

*Fertilizer Sources and Test Crop:* Fertilizers including urea (46-0-0), triple super phosphate (0-46-0), Potassium chloride (0-0-60), magnesium sulfate (28 % $SO_3^-$), EDTA Zinc (12 % Zn), and borax (11% B) were used as the source of nutrients for Nitrogen, Phosphorus, Potassium, Sulphur, Zinc, and Boron, respectively. Kuncho and Gibe varieties of tef were used as a test crop for experiments in rainy and irrigation seasons.

*Experimental Design:* This study was conducted on farmlands across different locations. The trial was arranged in a completely randomized design with three replications at each study site. The nutrient omission was used as a design of this experiment. During the rainy production season, the recommended Nitrogen and Phosphorus rates were used for nitisols and vertisols in the districts (Table 2). The treatments were composed of: one treatment which has six nutrients (N, P, K, S, Zn, and B). and the omitted of N, P, K, S, Zn, and B are composed of the remaining treatments in this trial. In addition, positive control (recommended NP), negative control (without fertilizer application), and $NPS_2$ (30 $Kgha^{-1}$) were used. $NPS_2$ treatment was used to support further evaluation of Sulphur fertilizer rate compared with NP fertilizers.

*Fertilizer Rates*

**Table 1. Rates of applied nutrients in vertisols and nitisols under the rainy season**

| No. | Treatment | Nutrient rates* (Kgha$^{-1}$) used in the treatment application | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | N | | $P_2O_5$ | | $K_2O$ | S | Zn | B |
| | | Vertisols | Nitisols | Vertisols | Nitisols | | | | |
| 1 | All (NPKSZnB) | 80 | 46 | 46 | 69 | 60 | 10.5 | 5 | 1 |
| 2 | All – B | 80 | 46 | 46 | 69 | 60 | 10.5 | 5 | 0 |
| 3 | All – Zn | 80 | 46 | 46 | 69 | 60 | 10.5 | 0 | 1 |
| 4 | All – S | 80 | 46 | 46 | 69 | 60 | 0 | 5 | 1 |
| 5 | All – K | 80 | 46 | 46 | 69 | 0 | 10.5 | 5 | 1 |
| 6 | All - P | 80 | 46 | 0 | 0 | 60 | 10.5 | 5 | 1 |
| 7 | RNP | 80 | 46 | 46 | 69 | 0 | 0 | 0 | 0 |
| 8 | No fertilizer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | RNP + $S_2$ | 80 | 46 | 46 | 69 | 0 | 30 | 0 | 0 |
| 10 | All – N | 0 | 0 | 46 | 69 | 60 | 10.5 | 5 | 1 |

**Note: the rate of NP is based on previous recommendations for each location.*

A total of nine treatments were used for irrigation production season which includes one All treatment with six nutrients (N, P, K, S, Zn, and B), and the other six treatments were composed by omitting N, P, K, S, Zn, and B. Moreover, positive control (recommended NP) and negative control (without fertilizer application) treatments were also comprised. The Nitrogen, and Phosphorus rates of 92, and 69 Kgha$^{-1}$ were used, respectively. The rate of Potassium, Sulphur, Zinc, and Boron nutrient rates was used as similar to the rainy season shown in Table 1.

*Experimental Management:* The agronomic practices were conducted based on recommendations. After preparing the fields, all the sites were planted with broadcasted and row for rainy and irrigation seasons, respectively. The fertilizer and seed rate had been calculated without considering furrow spaces for trials under irrigation. The irrigation water had been applied in furrows with 40 cm furrow width at 7-14 days irrigation intervals. All fertilizers were applied by band application at planting except three split urea for top dressing. The first split of Nitrogen was applied one month after emergence. Weed management was started just after 2 weeks after the emergence of the trials.

Each site has been weeded three times. All experimental sites of the rainy season were harvested from 15 November 2021 to 15 December 2021 whereas the experiment under irrigation was harvested in May 2021.

*Data Collection:* Composite soil samples from 0-20 cm soil depth were collected from each experimental field. Major soil parameters such as soil pH-$H_2O$, organic carbon (OC), available Phosphorus (AP), exchangeable acidity, and total Nitrogen (TN) analysis were conducted in Adet Agricultural Research Center's soil laboratory.

Measurements of plant height, panicle length, aboveground biomass, and grain yield were collected for this trial. The measurement of plant height was recorded from the soil surface to the tip of a spike from 10 randomly selected plants from the net plot area at physiological maturity. Panicle length was measured from 10 randomly selected plants. Harvesting was done from the middle 16 rows of 3 m by 3.2 m (9.6 $m^2$) net plot area, leaving the border rows as a barrier. Then, biomass was measured from harvested plants in the net plot area at the field using digital balance and then converted into Kg per hectare. Grain yield was also measured after threshing of collected biomass from the net plot area and then measured its weight by sensitive balance then converted into $Kgha^{-1}$. Finally, grain yield was adjusted by 12.5% moisture content.

Data Analysis: All collected samples were air-dried and crushed to pass a 2-mm sieve. Analyses were performed on surface samples including pH, organic C, total Nitrogen (N), available Phosphorus (P), and cation exchange capacity following standard soil laboratory procedures. Soil pH-H2O was determined in soil-water suspensions of 1:2.5 ratios (Lean, 1982). Available Phosphorus was also done following the Olsen method (Olsen, and Sommers, 1982) while total Nitrogen was done using the Kjeldahl method (Bremner, and Mulvaney, 1982). The wet oxidation method was used to determine soil organic carbon (Walkley, and Black, 1934). Cation exchange capacity was also determined by the ammonium acetate extraction procedures (Houba et al., 1986).

Analyses of variance were executed for grain yield and yield-related test crop data from each site and all sites combined in the district. A test of significance for the treatment was made for significant results as outlined by Cochran and Cox (1992) for situations with heterogeneous variance among treatments. Mean comparisons were done to compare positive control and other treatments. Graphs were generated using R software.

**Results and Discussion**

*Soil Chemical Properties of the Experimental Area:* The results of the nutrient analysis of soils are displayed in Table 2. The experimental sites of vertisols were observed with a pH range of 6.0-6.9, which is slightly acidic (Tekalign *et al*., 1991). The pH of nitisols was also found between 5.1 to 5.9 which is moderately acidic. In the study area, the highest and lowest mean soil pH values of 6.49 and 5.13 in the top 20 cm soil depth were found under vertisols and nitisols, respectively (Table 2). The result confirms that nitisols were more acidic than vertisols. The total Nitrogen content of the soil of experimental sites varied from 0.06-0.14% and from 0.08-0.18 % in nitisols and vertisols, respectively. The soil has low to medium N contents according to the rating by Tekalign (1991). Relatively vertisols have lower Nitrogen content which is associated the higher Nitrogen loss in soil nature. The organic carbon content of the soil was between 0.7-1.3 and 1.0-2.2 % for vertisols and nitisols, respectively. The soil organic carbon is ranged between low to medium study soils as per criteria developed by Tekalign *et al*., (1991).

**Table 2. Soil parameters descriptive statistics at planting time across sites of study districts under rainy and irrigation production seasons (2021/22)**

| Variation | pH | OC* (%) | P (mgKg$^{-1}$) | CEC (cmol/Kg) | TN (%) |
|---|---|---|---|---|---|
| | | | Vertisols [Rainy season] | | |
| Minimum | 6.02 | 0.70 | 4.31 | 41.56 | 0.06 |
| Maximum | 6.86 | 1.28 | 5.69 | 59.20 | 0.14 |
| Mean | 6.49 | 1.00 | 5.11 | 49.16 | 0.12 |
| Rating | Slightly acid | Low-medium | Very low-low | High-very high | Medium-high |
| | | | Nitisols [Rainy season] | | |
| Minimum | 5.13 | 0.95 | 5.25 | 24.62 | 0.08 |
| Maximum | 5.88 | 2.20 | 14.80 | 39.52 | 0.18 |
| Mean | 5.39 | 1.89 | 8.87 | 29.80 | 0.15 |
| Rating | Moderately acid | Low_ medium | Low-high | High-very high | Medium-high |
| | | | Nitisols [Irrigation season] | | |
| Site 1 | 5.01 | 1.76 | 7.15 | - | 0.13 |
| Site 2 | 5.42 | 1.76 | 35.74 | - | 0.14 |
| Mean | 5.22 | 1.76 | 21.44 | - | 0.14 |
| Rating | Strongly acid | Medium | Medium-high | - | Medium |
| Critical | 5.50 | 2.00 | 10.00 | - | 0.20 |
| Reference | (Tekalign *et al.*, 1991) | (Tekalign *et al.*, 1991) | (Olsen *et al.*, 1954) | FAO (2006) | (Tekalign *et al.*, 1991) |

** CEC: cation exchange capacity, P: available Phosphorus, OC: organic carbon, TN: total Nitrogen content.*

The available Phosphorus content of the soil of the experimental site was 4.3-5.7 and 5.3-14.8 mgKg$^{-1}$, respectively which lies in a range of deficiency for vertisols (Olsen *et al.,* 1954). It ranged from medium-high for nitisols in the study area. However, the available p content in the soil at trial sites in the irrigation command area is higher, ranging from 7.2 to 35.4 mgKg$^{-1}$. This may be related to P fertilizer addition build-up during both production seasons. The cation exchange capacity value of both soils is high to very range according to the rating by Hazelton and Murphy (2019). This tells that the addition of chemical fertilizer is needed for improving tef yield in study sites.

*Response of Tef Yield to Applied Nutrients:* Grain yield significantly ($p \leq 0.01$) varied to omitted nutrient types compared to the negative control and All-N treatments during the rainy season. Grain yield was also significantly ($p \leq 0.01$) affected by recommended Nitrogen and Phosphorus compared to no fertilizer treatment. Compared to treatments that got all types of nutrients (NPSBZnK), certain sites had highly significant ($p \leq 0.01$) higher yields (Table 4). However, the grain yield of tef was not significantly ($p > 0.05$) increased with the application of KSZnB with NP compared to NP alone. Our finding was in disagreement with Gebrehawariyat *et al.,* (2018) who suggested that applying K fertilizer increases tef production.

A higher tef yield was recorded from All-B (1695 Kgha$^{-1}$) in nitisols at site 7 and All-Zn (1712 Kgha$^{-1}$) in vertisols at site 4 (Table 3). However, the lower yield obtained from no fertilizer treatment ranged from 209 to 432 Kgha$^{-1}$ across the studied sites. As we can see from our study, the majority of plant nutrients (KSZnB) come from the soil, but the soil did not provide an adequate amount of all the nutrients, particularly the Nitrogen and Phosphorus that plants need in the proper amounts. Nitrogen is the most yield-limiting nutrient in most soils, agroecology, and regions (Amare , 2022; Alemayehu , 2022). It is also a universal yield-limiting nutrient (Yara, 2018). So, synthetic Nitrogen fertilizers accounted for the food increase in the world. Different studies indicate that crops grieve a severe N deficit and reduced yields as a result of inadequate amounts of Nitrogen and other nutrients (Cassman and Dobermann, 2022). This might be associated with applied NP fertilizer and native soil nutrients being severely eroded in agricultural fields *(Haileslassie et al.,* 2005). Our research contradicts assertion of Habte and Boke (2017) that NPS had increased tef yield. Furthermore, our findings conflict with those of Kihara *et al,* (2020), who claimed that African soils are deficient in micronutrients. Biological yield results had a direct correlation with the locations where our soil analysis revealed low Nitrogen and Phosphorus concentrations in trial sites. Thus, fertilization is mandatory to address deficiencies.

**Table 3. Tef grain yield (Kgha$^{-1}$) response to nutrient types at different sites in GonjiKolela, Yilmana Densa, and Hulet Ejuenbesie districts (2021/22)**

| Treatments | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 | Site 8 | Site 9 | Site 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| All* | 1440 | 1629 | 1264 | 1508 | 973 | 933 | 1141 | 1039 | 1323 | 1443 |
| All-B | 1438 | 1695 | 905 | 1547 | 1023 | 1078 | 1209 | 1088 | 1179 | 1652 |
| All-Zn | 1346 | 1569 | 1470 | 1712 | 938 | 1065 | 1138 | 957 | 1258 | 1328 |
| All-S | 1349 | 1446 | 1120 | 1618 | 1127 | 1104 | 1110 | 1011 | 1138 | 1415 |
| All-K | 1215 | 1675 | 1190 | 1473 | 1147 | 1076 | 1231 | 887 | 1198 | 1393 |
| All-P | 1330 | 1372 | 1356 | 1660 | 369 | 829 | 1030 | 1013 | 1162 | 1139 |
| RNP | 1044 | 1552 | 1260 | 1613 | 1154 | 1118 | 1202 | 974 | 1218 | 1144 |
| NF | 432 | 418 | 209 | 398 | 253 | 571 | 469 | 526 | 440 | 448 |
| RNP+$S_1$ | 1292 | 1568 | 1182 | 1506 | 986 | 967 | 1135 | 1032 | 1131 | 1305 |
| All-N | 547 | 490 | 232 | 804 | 312 | 728 | 663 | 485 | 543 | 557 |
| LSD (5%) | 287 | 354 | 277 | 337 | 156 | 242 | 305 | 221 | 242 | 258 |
| CV | 14.6 | 15.4 | 15.9 | 14.2 | 11.0 | 15.0 | 17.4 | 14.4 | 13.4 | 13.0 |
| SEM | ±71.4 | ±91.5 | ±83.1 | ±81.2 | ±66.8 | ±38.9 | ±52.7 | ±42.8 | ±58.0 | ±72.4 |
| p | *** | *** | *** | *** | *** | ** | *** | *** | *** | *** |

**All= NPKSZnB, CV = coefficient of variance, LSD= least significant difference, NF= no fertilizer, RNP= recommended N and P, RNP+$S_1$= recommended N and P with the addition of 30 Kgha$^{-1}$ S, SEM= standard error of the mean, ***: significant at 0.1%.*

Overall grain yield of tef had significantly ($p \leq 0.01$) varied with the application of different plant nutrients across districts. Response to omitted plant nutrients significantly varied with the interaction effect of nutrient types across sites (Table 3). It shows the presence of variability across sites. The mean grain yield highly significantly ($p \leq 0.001$) increased in response to plant nutrient application compared with All-N and control across all trial sites vertisols of study districts (Figure 1). Figure 1 also displays that the grain yield was also significantly ($p \leq 0.001$) different in the omission of nutrient types. Generally, the higher yield was witnessed from All-Zn and All in vertisols. A non-significant ($p > 0.05$) grain yield increments were observed from Potassium, Sulphur, Zinc, and Boron omitted fertilizers in vertisols and nitisols (Figure 1).

The highest (1241 Kgha$^{-1}$) and the lowest (491 Kgha$^{-1}$) grain yields were recorded from All-Zn and no fertilizer treatments in nitisols, whereas the maximum (1407 Kgha$^{-1}$) and the minimum (342 Kgha$^{-1}$) grain yields were obtained from All-Zn and no fertilizer treatments in vertisols. The All-N treatment gave a lower yield following negative control for both soil types. The production of tef is not limited by the absence of P nutrient application in vertisols. This result contradicts those of Alemayehu *et al.*, (2022) who found that P limits the amount of tef productivity in vertisols.

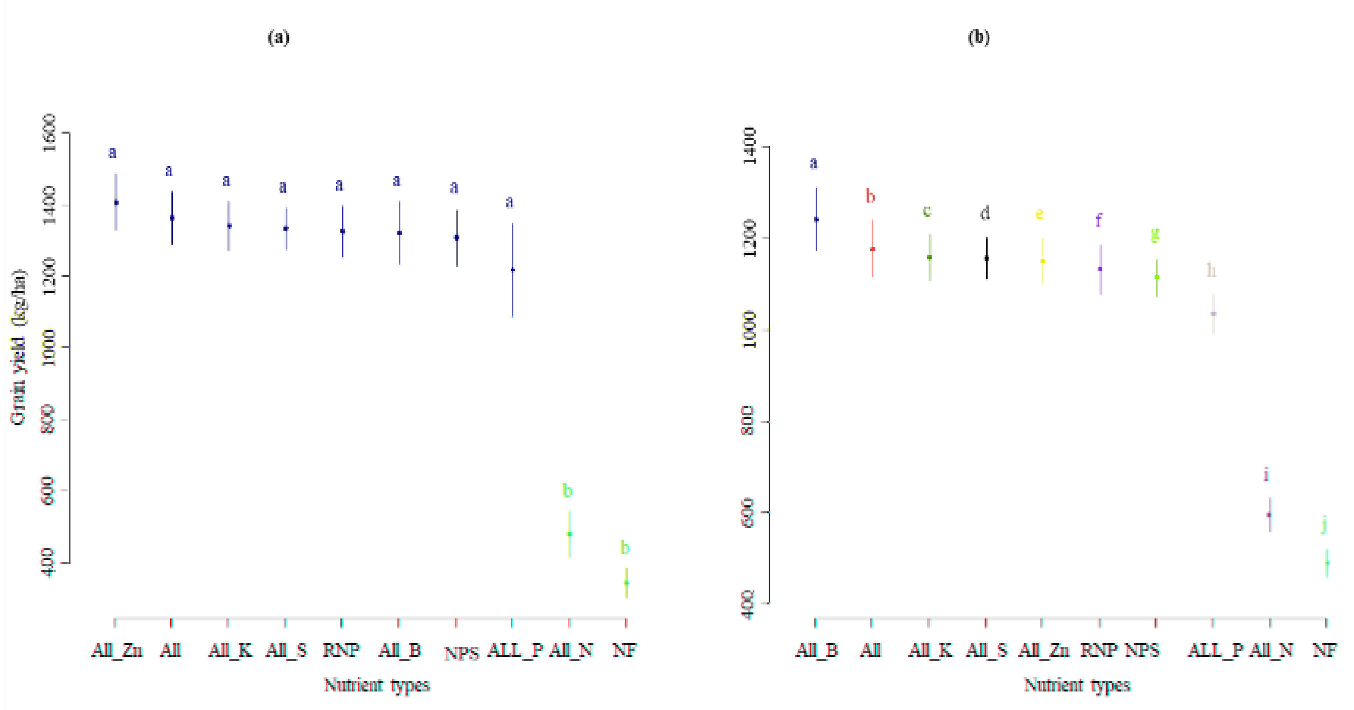


Figure 6. The combined analysis of tef yield response to nutrients in a) vertisols and b) nitisols of Yilmana Densa, Gonji Kolela, and Hulet Ejuenebsie districts under rainfed production system. Short lines at the top of each bar represent the standard error of lime amendment, lowercase letters indicate significant differences ($p<0.05$) among treatments.

The absence of KSZnB nutrients resulted in nearly comparable grain yields with the only application of recommended NP and All fertilizers in both soil types under rainfed production season. This shows that currently, the soil can supply those nutrients without limiting them (Amare *et al.*, 2018; and 2019; Alemayehu *et al.*, 2022; Chala *et al.*, 2022). G. Selassie *et al.*, (2020) also demonstrated that K fertilizer cannot increase agricultural crop productivity in North West Ethiopia, which supports our findings. However, the result differed from the previous findings which show Ethiopian soils are deficient in macronutrients (KS) and some micronutrients (Abera and Kebede, 2013; Hailu *et al.*, 2015; EthioSIS, 2016). Tesfaye *et al.*, (2021), who reported that the application of blended NPS and K fertilizer increases crop productivity in Southern Ethiopia, did not support our findings. The result reached by Brhane *et al.*, (2017) that the application of K fertilizer boosts the yield of cereal crops in vertisols in the northern part of Ethiopia is also in disagreement with our findings.

*Response of Tef to Nutrient Types under Irrigation Production System:* Both grain and biomass yields showed highly significant ($p \leq 0.01$) differences among treatments at all experimental sites under the irrigation production system. Table 4 indicates that the application of Nitrogen and Phosphorus nutrients at both sites resulted in greater grain yields of 1693 and 1835 $Kgha^{-1}$. The minimum grain yield (1053 and 1151 $Kgha^{-1}$) was observed from no fertilizer treatment. From sites 1 and 2, the N omitted treatment also contributed grain yields of 1501 and 1184 $Kgha^{-1}$, respectively. The observed significant difference among treatment means for grain and biomass yields was caused by the omission of N and P as well as control treatments (no fertilizer) when comparing them with other remaining omitted nutrient treatments. Different soil characteristics at the trial sites showed up in variable responses to grain and biomass yield. This showed that NP nutrients have the main role in tef biological yield determination under irrigation systems which is a similar result to main season tef production (Acharya *et al.*, 2020; Alemayehu *et al.*, 2022; Chala *et al.*, 2022) stated N is limiting nutrient for crop productivity.

**Table 4. The combined analysis of grain and biomass yield ($Kgha^{-1}$) response to applied nutrients under irrigation in Mecha district**

| Treatments | Grain yield | | Biomass yield | |
|---|---|---|---|---|
| | Site 1 | Site 2 | Site 1 | Site 2 |
| All* | 1584.8 | 1741 | 5111.1 | 5486.1 |
| All-B | 1659.7 | 1972.2 | 5930.6 | 5486.1 |
| All-Zn | 1605.8 | 1656.9 | 5601.9 | 5277.8 |
| All-S | 1397.6 | 1926 | 5138.9 | 5486.1 |
| All-K | 1512.7 | 1600.3 | 4949.1 | 4791.7 |
| All-P | 1079.6 | 1971.9 | 4122.2 | 5694.4 |
| RNP | 1693.2 | 1835.1 | 6034.7 | 5555.6 |
| NF | 1052.5 | 1150.7 | 3402.8 | 2986.1 |
| All-N | 1501.4 | 1184 | 5083.3 | 3263.9 |
| p | ** | ** | ** | ** |
| LSD | 308.8 | 347.6 | 1248.6 | 896.7 |
| CV | 12.4 | 12.1 | 14.4 | 10.7 |

**All= NPKSZnB, CV = coefficient of variance, LSD= least significant difference, NF= no fertilizer, RNP= recommended N and P, **: significant at 1%.*

Similar to the individual experimental sites from the combined statistical analysis result showed that both grain and biomass yields of tef showed highly significant differences among treatment

Similarly, the omission of Phosphorus fertilizer also reduced a grain yield of tef by 12 and 10% in nitisols and vertisols, respectively. It might be related to the native soil stock's limited availability of plant nutrients, specifically its low Nitrogen and Phosphorus concentration, as seen in Figure 2. This finding agreed with many research reports which revealed that Nitrogen is the first and most limiting nutrient for tef production followed by Phosphorus in vertisols of Ethiopia (Girma *et al.*, 2012; Amare *et al.,* 2018; 2019; Alemayehu *et al.,* 2022). Thus, N deficiency can be corrected by Nitrogen fertilization and soil management (Atkinson *et al.,* 2005; Guignard *et al.,* 2017). Nevertheless, from the applied Nitrogen between 30 and 50% is taken up by cereal crops *(Omara et al.,* 2019). Future research is required to improve Nitrogen fertilization efficiency via different technologies. From global fertilizer total consumption, 57% of Nitrogen is demanded followed by Phosphorus (24%) to increase grain yield (Heffer *et al.,* 2017; Yara, 2018). This indicates that Nitrogen is also the most significant key nutrient in the world. However, our finding disagreed with Yara (2018) and Heffer *et al.,* (2017) who reported that Potassium (19%) fertilizers are looked-for and applied to improve crop quality. Therefore, every year application of Nitrogen is mandatory to sustain yield and biomass production.

Nutrient deficiency is a serious threat to Ethiopian soils, particularly Nitrogen and Phosphorus (Hailu *et al.,* 2015). It is also an eminent critical yield-limiting nutrient to agricultural crop production in the world particularly in the tropics due to the fluctuation of temperature and precipitation (Zhaohui *et al*., 2012; Guignard *et al.,* 2017). According to Singh (2008), widespread multi-nutrient deficiencies and deteriorating soil health are the cause of low nutrient use efficiency, productivity, and profitability. So, the right use of yield-limiting nutrients in crop production is crucial for increasing crop yield and quality, environmental safety, and economic considerations (Rütting *et al.,* 2018).

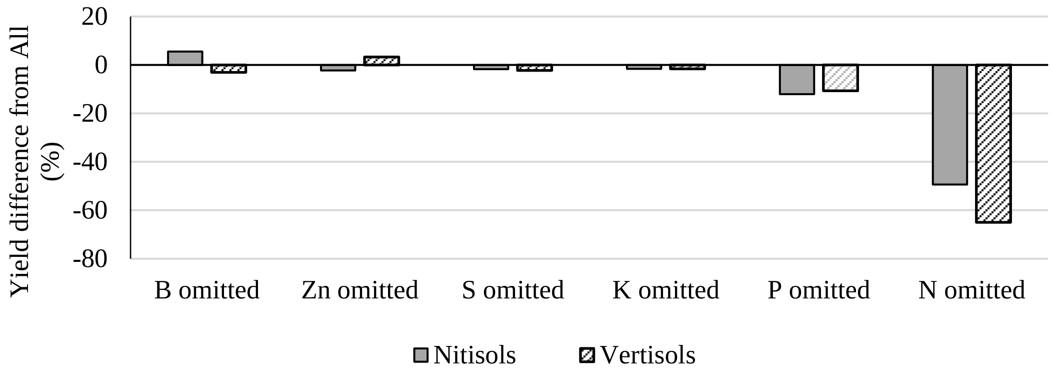


**Figure 7.** The difference Tef yield-limiting nutrients in percentage to the response of each nutrient to all applied nutrient types in study soils under rainfed production system.

Phosphorus is the second essential plant nutrient for global food production (Roberts and Johnston, 2015). Only 10 to 15% of applied P fertilizer is taken by crops this tells that it must be applied to feed the ever-increasing population. The residual P fertilizer is not recovered by the crop due to its change into the unavailable form). To meet the goal of the productivity and profitability of food crop production, 4R nutrient stewardship strategies are critically important (Bruulsema *et al.*, 2019). Thus, optimizing nutrient management practices and technologies is required in our agricultural crop production systems under rainfed and irrigation seasons.

The omission of Boron improved tef yield by 5.5% in nitisols whereas Zn omission increased tef grain yield by 3.2% in vertisols (Figure 4). This indicates that Zn in vertisols and B in nitisols are adequately available in soil nutrient stock. Below 2% non-significant yield decrements were observed when Potassium and Sulphur fertilizers are omitted which shows that they are supplied by the indigenous soil.

The omission of Nitrogen diminishes grain and biomass yields by 19 and 21% under irrigation, respectively. Without fertilizer (control) grain and biomass yield declined by 34 and 40%, respectively. A non-significant less than 10% yield reduction was observed when P, K, S, and Zn fertilizers were omitted under the irrigation production system. However, the omission of B increases the tef yield by 9 % in nitisols under irrigation season. The result is supported by the result of our finding in nitisols under the rainy season production system. This shows that Nitrogen is also the major required nutrient type for tef under irrigation. Our finding is in line with the results found under the main season crop production system in the region.

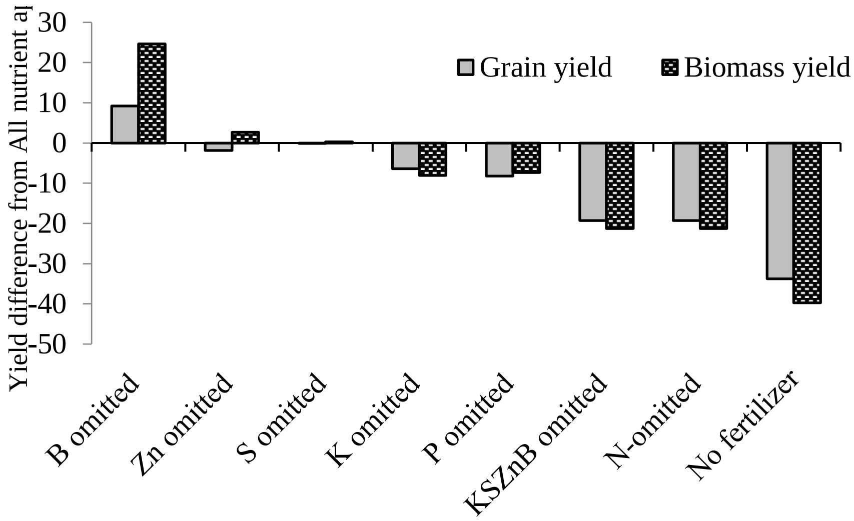


**Figure 8.** The difference Tef yield-limiting nutrients in percentage to the response of each nutrient to all applied nutrient types in study soils under irrigation production system.

Phosphorus was not limiting nutrient of tef productivity under Koga irrigation scheme, Mecha district. The grain yield result is directly expressed the before planting soil result where available Phosphorus content of the soil was ranged high. This might be associated with the accumulation of residual Phosphorus due to higher application of P fertilizer under two production seasons (rainfed and irrigation).

*Relationship between Applied Nutrients and Tef Biological Parameters:*In different applied fertilizers, the grain yield was significantly and positively correlated with biomass (r=0.94***), plant height (r=0.80***), and panicle length (r=0.63***) whereas it was inversely and significantly correlated with harvest index with a correlation coefficient of 0.46***, and 1000-seed weight with r = -0.45 at $p < 0.001$ (Figure 4). Generally, fertilizer application and crop yields often have a very positive relationship. Aboveground biomass, plant height, and panicle length are the most crucial yield attribute parameters in the tef fertilizer study which contributes to grain. Alemayehu *et al.*, (2022), following our findings, that tef yield, and applied nutrients had a significant influence on the yield component parameters.

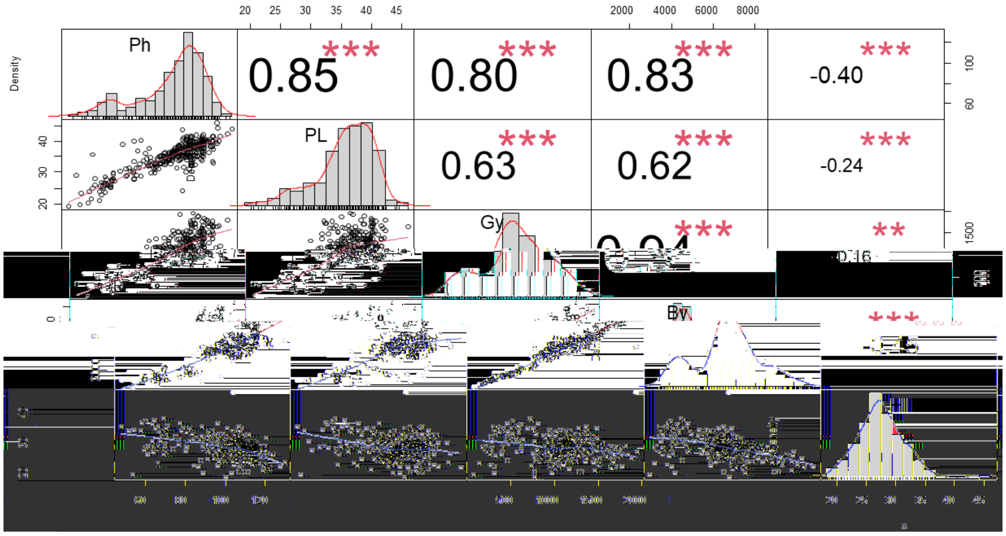


**Figure 9.** Correlation of yield and yield components of tef under applied nutrient types across sites in North West Amhara (2021/22). Ph: plant height, PL: panicle length, Gy: grain yield, By: biomass yield; HI: Harvest index, **: significant at 5% and *** significant at 1%. The numbers in the figure indicate the correlation coefficient values.

## Conclusions and Recommendations

In this study, a significant biological yield advantage was recorded from the recommended Nitrogen and Phosphorus but, the yield was not improved due to the application of K, S**,** Zn, and B nutrients. Tef yield obtained from Nitrogen omitted treatment was equivalent to the yield attended from no fertilizer added treatment although all other nutrients were applied in optimal levels at N omitted treatment. Nitrogen is the first and major limiting nutrient for tef production in all the district soil types under rainfed and irrigation production systems. Next to N, Phosphorus is also a critical nutrient to produce tef grain yield in nitisols under rainfed production. The role of Potassium, Sulphur, Zinc, and Boron nutrients are not mandatory compared to Nitrogen and Phosphorus for tef production. The investigation of Nitrogen and Phosphorus fertilizer rate is required to know the optimum production curve.

**Acknowledgments**

This study was financed by the All Ethiopian-coordinated Fertilizer Research (AECFR) project. We are grateful to the farmers who allowed us to implement our multilocation experiments on their cropland because it was crucial to the success of this study.

**References**

Abera, Y., and Kebede, M. (2013). *Assessment on the Status of Some Micronutrients in Vertisols of the Central Highlands of Ethiopia*. *1*(1), 15–19.

Acharya, N. R., Sah, S. K., Gautam, A. K., and Regmi, A. P. (2020). Response of Nutrient Omission and Irrigation Scheduling on Growth and Productivity of Maize. *International Journal of Applied Sciences and Biotechnology*, *8*(3), 343–354. https://doi.org/10.3126/ijasbt.v8i3.31612

Alemayehu, B., Adgo, E., and Amare, T. (2022). Nutrients Limiting Tef [Eragrostis tef (Zucc.) Trotter] Crop Yield on Vertisols in Yilmana Densa, Upper Blue Nile Basin of Ethiopia. *Journal of Plant Growth Regulation 2022*, 1–13. https://doi.org/10.1007/S00344-022-10741-Y

Amare, T., Alemayehu, A., Kerebih, B., Bazie, Z., Erikhun Alemu, A. D., Tesfaye Feyisa, A. G., Sefinew Wale, A., and Getaneh, D. (2019). Verification of crop responses to Potassium and Zinc and Boron-containing fertilizers in the Northwestern Amhara Region. *Adaptation and Generation of Agricultural Technologies*, 148–161.

Amare, T., Alemu, E., Bazie, Z., Woubet, A., Kidanu, S., Alemayehu, B., Awoke, A., Derebe, A., Feyisa, T., Tamene, L., Kerebh, B., Wale, S., and Mulualem, A. (2022). Yield-limiting plant nutrients for maize production in northwest Ethiopia. *Experimental Agriculture*. https://doi.org/10.1017/S0014479721000302

Amare, T., Bazie, Z., Alemu, E., Wubet, A., Agumas, B., Muche, M., Tesfaye Feyisa, A., and Desalew Fentie. (2018). Crops Response to Balanced Nutrient Application in Northwestern Ethiopia Tadele. *Blue Nile Journal of Agricultural Research*, *1*(1), 1–14.

Assefa, K., Yu, J. K., Zeid, M., Belay, G., Tefera, H., and Sorrells, M. E. (2011). Breeding tef [Eragrostis tef (Zucc.) trotter]: Conventional and molecular approaches. *Plant Breeding*, *130*(1), 1–9. https://doi.org/10.1111/j.1439-0523.2010.01782.x

Baye, K. (2014). Synopsis : Tef : nutrient composition and health benefits. In *Ethiopia Strategy Support Program* (Issue 67).

Bekele, D., Gebreselassie, Y., and Tadesse, T. (2022). Yield Response of Upland Rice (oryza sativa l.) Through Nutrient Omission Trial in Vertisols of Fogera Districts. *American Journal of Plant Biology*, *7*(1), 30–40. https://doi.org/10.11648/j.ajpb.20220701.15

Belachew, K. Y., Maina, N. H., Dersseh, W. M., Zeleke, B., and Stoddard, F. L. (2022). Yield Gaps of Major Cereal and Grain Legume Crops in Ethiopia: A Review. *Agronomy*, *12*(10). https://doi.org/10.3390/agronomy12102528

Beyene, D. (1983). *Micronutrient status of some Ethiopian soils*. http://197.156.72.153:8080/xmlui/handle/123456789/831

Brhane, H., Mamo, T., and Teka, K. (2017). Optimum Potassium fertilization level for growth, yield and nutrient uptake of wheat (Triticum aestivum) in Vertisols of Northern Ethiopia. *Cogent Food and Agriculture*, *3*(1). https://doi.org/10.1080/23311932.2017.1347022

Bruulsema, T. W., Peterson, H. M., and Prochnow, L. I. (2019). The Science of 4R Nutrient Stewardship for Phosphorus Management across Latitudes. *Journal of Environmental Quality*, *48*(5), 1295–1299. https://doi.org/10.2134/jeq2019.02.0065

Cassman, K. G., and Dobermann, A. (2022). Nitrogen and the future of agriculture: 20 years on: This article belongs to Ambio's 50$^{th}$ Anniversary Collection. Theme: Solutions-oriented research. *Ambio*, *51*(1), 17–24. https://doi.org/10.1007/s13280-021-01526-w

Chala, G., Kassa, S., Tadele, T., Assefa, K., Teshome, H., Agegnehu, G., Abera, W., Tibebe, D., Sileshi, G. W., and Erkossa, T. (2022). Yield response of tef ( Eragrostis tef ) to Nitrogen, Phosphorus, Potassium and sulphur under balanced fertilization on Vertisols in different agroecological zones of Ethiopia . *Experimental Agriculture*, 1–14. https://doi.org/10.1017/s0014479722000114

Chamberlin, J., Jayne, T. S., and Snapp, S. (2021). The role of active soil carbon in influencing the profitability of fertilizer use: Empirical evidence from smallholder maize plots in Tanzania. *Land Degradation and Development*, *32*(9), 2681–2694. https://doi.org/10. 1002/ldr.3940

Cochran, W. G. and Cox, G. M. (1992). *Experimental designs*. 611.

Dargie, S., Girma, T., Chibsa, T., Kassa, S., Boke, S., Abera, A., Haileselassie, B., Addisie, S., Amsalu, S., Haileselassie, M., Soboka, S., Abera, W., and Weldesemayat, S. G. (2022). Balanced fertilization increases wheat yield response on different soils and agroecological zones in Ethiopia. *Experimental Agriculture*, *58*(July). https://doi.org/10.1017/S0014479722000151

EthioSIS, (Ethiopian Soil InformationSystem). (2016). *Soil Fertility Status and Fertilizer Recommendation Atlas of Amhara National Regional State, Ethiopia.*

G.Selassie, Y., Molla, E., Muhabie, D., Manaye, F., and Dessie, D. (2020). Response of crops to fertilizer application in volcanic soils. *Heliyon*, *6*(12), e05629. https://doi.org/10.1016/j.heliyon.2020.e05629

Gebrehawariyat, F. M., Haile, W., Mamo, T., Zipori, I., and Sokolowski, E. (2018). Response of tef [Eragrostis tef (Zucc.) Trotter] to Potassium fertilizer application in four districts of North Shewa, Ethiopia. *Electronic International Fertilizer Correspondent (e-Ifc), No.53*, 3–15.

Girma, K., Reinert, M., Ali, M. S., Sutradhar, A., and Mosali, J. (2012). Nitrogen and Phosphorus Requirements of Tef Grown Under Dryland Production System. *Crop Management*, *11*(1), 1–14. https://doi.org/10.1094/cm-2012-0319-02-rs

Guignard, M. S., Leitch, A. R., Acquisti, C., Eizaguirre, C., Elser, J. J., Hessen, D. O., Jeyasingh, P. D., Neiman, M., Richardson, A. E., Soltis, P. S., Soltis, D. E., Stevens, C. J., Trimmer, M., Weider, L. J., Woodward, G., and Leitch, I. J. (2017). Impacts of Nitrogen and Phosphorus: From genomes to natural ecosystems and agriculture. *Frontiers in Ecology and Evolution*, *5*(JUL). https://doi.org/10.3389/fevo.2017.00070

Habte, M., and Boke, S. (2017). Influence of balanced nutrients on growth performance and yield of Tef (Eragrostis tef (Zucc.)) in the midland of Bensa, Southern Ethiopia. *Journal of Scientific and Innovative Research*, *6*(3), 101–103. https://doi.org/10.31254/jsir.2017.6303

Haileslassie, A., Priess, J., Veldkamp, E., Teketay, D., and Lesschen, J. P. (2005). Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agriculture, Ecosystems and Environment*, *108*(1), 1–16. https://doi.org/10.1016/j.agee.2004.12.010

Hailu, H., Mamo, T., Keskinen, R., Karltun, E., Gebrekidan, H., and Bekele, T. (2015). Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia. *Agriculture and Food Security*, *4*(1), 1–10. https://doi.org/10.1186/s40066-015-0038-0

Halpern, M., Gashu, K., Zipori, I., Saranga, Y., and Yermiyahu, U. (2021). Tef (Eragrostis tef) responses to Phosphorus and Potassium fertigation under semi-arid mediterranean climate. *Agronomy*, *11*(8), 1–17. https://doi.org/10.3390/agronomy11081588

Hazelton, P., and Murphy, B. (2019). Interpreting Soil Test Results. *Interpreting Soil Test Results*. https://doi.org/10.1071/9781486303977

Heffer, P., Gruère, A., and Roberts, T. (2017). Assessment of fertilizer use by crop at the global level 2014-2014/15. In *International Fertilizer Association and International Plant Nutrition Institute*.

Hurni, H. (1993). *World Soil Erosion and Conservation: Land degradation, famine, and land resource scenarios in Ethiopia* (In: Piment). World Soil Erosion and Conservation.

IFDC. (2015). Assessment of Fertilizer Consumption and Use By Crop in Ethiopia. In *IFDC*. https://ifdcorg.files.wordpress.com/2015/04/ethiopia-fertilizer-assessment.pdf

IFPRI, (International Food Policy Research Institute). (2010). *Fertilizer and Soil Fertility Potential in Ethiopia*.

Johnston, A. M., and Bruulsema, T. W. (2014). 4R nutrient stewardship for improved nutrient use efficiency. *Procedia Engineering*, *83*, 365–370. https://doi.org/10.1016/j.proeng.2014. 09.029

Ketema, S. (1997). Promoting the conservation and use of underutilized and neglected crops. In *Frontiers in Plant Science* (Vol. 8, Issue March).

Kihara, J., Bolo, P., Kinyua, M., Rurinda, J., and Piikki, K. (2020). Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops. *Environmental Geochemistry and Health*, *42*(9), 3015–3033. https://doi.org/10.1007/s10653-019-00499-w

Olsen, S. R. ., Cole, C. V. ., Watanabe, F. S. . and, Dean, L. A. (1954). *Estimation of Available Phosphorus in Soils by Extraction with Sodium Sterling Robertson Olsen - Google Books* (No.

939).

Omara, P., Aula, L., Oyebiyi, F., and Raun, W. R. (2019). World Cereal Nitrogen Use Efficiency Trends: Review and Current Knowledge. *Agrosystems, Geosciences and Environment*, *2*(1), 1–8. https://doi.org/10.2134/age2018.10.0045

Pradhan, P., Fischer, G., Van Velthuizen, H., Reusser, D. E., and Kropp, J. P. (2015). Closing yield gaps: How sustainable can we be? *PLoS ONE*, *10*(6), 1–18. https://doi.org/10.1371/journal.pone.0129487

Rakshit, A., Abhilash, P. C., And, H. B. S., and Ghosh, S. (2017). *Adaptive Soil Management: From Theory to Practices*. Springer Nature. https://doi.org/10.1007/978-981-10-3638-5

Roberts, T. L., and Johnston, A. E. (2015). Phosphorus use efficiency and management in agriculture. *Resources, Conservation and Recycling*, *105*, 275–281. https://doi.org/10.1016/j.resconrec.2015.09.013

Rütting, T., Aronsson, H., and Delin, S. (2018). Efficient use of Nitrogen in agriculture. *Nutrient Cycling in Agroecosystems*, *110*(1), 1–5. https://doi.org/10.1007/s10705-017-9900-8

Shewangizaw, B., Gurumu, G., Agegnehu, G., Eshetu, M., Assefa, S., Hadgu, F., Seid, J., Tibebe, D., Sileshi, G. W., and Tamene, L. (2021). Yield response of barley to the application of mineral fertilizers containing major nutrients on Cambisols and Vertisols in Ethiopia. *Experimental Agriculture*, *58*(13), 2022. https://doi.org/10.1017/S0014479721000223

Sileshi, G. W., Kihara, J., Tamene, L., Vanlauwe, B., Phiri, E., and Jama, B. (2022). Unravelling causes of poor crop response to applied N and P fertilizers on African soils. *Experimental Agriculture, 58*, 1–17. https://doi.org/10.1017/S0014479721000247

Singh, M. V. (2008). Micronutrient deficiencies in crops and soils in India. *Micronutrient Deficiencies in Global Crop Production*. https://doi.org/10.1007/978-1-4020-6860-7_4

Tanner, D. G., and Hulluka, M. (1991). Wheat Research in Ethiopia. In *Institute of Agricultural Research*.

Tekalign, T., I. Haque, A., and Aduayi, E. A. (1991). *Soil, plant, water, fertilizer, animal manure and compost analysis manual.pdf* (No. B13).

Tesfaye, T., Laekemariam, F., and Habte, A. (2021). Response of Bread Wheat (Triticum aestivum L.) to Potassium (K) and Blended NPS Fertilizer Rates in the Nitisols of Southern Ethiopia. *Applied and Environmental Soil Science*, *2021*. https://doi.org/10.1155/2021/8868940

William R. Ram, A., and Johnson, G. V. (1999). Improving Nitrogen Use Efficiency for Cereal Production. *Agronomy Journal*, *91*(3), 357–363. https://doi.org/10.1002/j.18793479.1975 .tb00325.x

Yara. (2018). Yara Fertilizer Industry Handbook. In *Yara* (Issue October, p. 90).

Yirga, C., and Hassan, R. M. (2013). Determinants of Inorganic Fertiliser Use In The Mixed Crop-Livestock Farming Systems of Central Highlands of Ethiopia. *African Crop Science Journal*, *21*(Supplement s3), 669–681.

Zelleke, G., Agegnehu, G., Abera, D., and Rashid, S. (2010). Fertilizer and Soil Fertility Potential in Ethiopia Table of Contents. In *Fertilizer and Soil Fertility Potential in Ethiopia*.

Zhaohui, L., Xiaozong, S., Lihua, J., Haitao, L., Yu, X., Xinhao, G., Fuli, Z., Deshui, T., Mei, W., Jing, S., Yuwe, S., Yuwen, S., Zhaohui, L., Xiaozong, S., Lihua, J., Haitao, L., Yu, X., Xinhao, G., Fuli, Z., … Yuwen, S. (2012). Strategies for Managing Soil Nitrogen to Prevent Nitrate-N Leaching in Intensive Agriculture System. *Soil Health and Land Use Management*, 133–154. https://doi.org/10.5772/29419