Research Article

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Effect of potassium fertilizer application in teff yield and nutrient uptake on Vertisols in the central highlands of Ethiopia

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Abstract: Teff is the most dominant staple cereals in Ethiopia, but yield levels are extremely low (1.2 t/ha) because of declining soil fertility, resulting in widespread national food insecurity. The aim of this study was to explore the effect of potassium (K) fertilization on teff yield and nutrient uptake in Vertisols in the central highlands of Ethiopia. Five levels of K (0, 30, 60, 90, and 120 K2O kg/ha) were applied as muriate of potash (KCl) arranged in RCBD with three farm fields as replicates. At crop maturity, a plot of 3 m × 3 m was harvested to measure teff yield and yield components and subsampled for laboratory analysis to determine nutrient uptake. Results showed a highly significant ($p < 0.01$) response of teff to K fertilizer application and significant differences among locations. When averaged across locations, the highest mean grain (1,875 kg/ha) and straw yields (6,774 kg/ha) were obtained with the application of 90 and 120 K2O kg/ha, respectively. However, the lowest grain (1,576 kg/ha) and straw (5,798 kg/ha) yields were harvested from control plots. This is about a 20% increase over the control. When averaged for all treatments, the highest mean grain (2,641 kg/ha) and straw (7,794 kg/ha) yields were obtained at Moretina Jiru and the lowest grain (1,280 kg/ha) and straw (4,210 kg/ha) yields were obtained at Sululta. Contrary to the popular view that Ethiopian Vertisols are rich in K, there are sites in the central highlands where K deficiency is limiting teff production. In sites where K-soil level was low and rainfall distribution was adequate, the application of K fertilizer along with the government recommended zinc blend fertilizer – NPSZn: 17.7 N + 35.3 P2O5 + 6.5 S + 2.5 Zn – significantly improves nutrient uptake, agronomic efficiency, and teff yields.

Keywords: agronomic efficiency, *Eragrostis tef* Zucc, highlands of Ethiopia, NPSZn blend, teff yields

1 Introduction

Agriculture is an engine for the economic growth in Ethiopia, currently accounting for 42% of the country’s GDP and more than 80% of its export earnings [1]. However, the sector is characterized by persistent low crop yields, constituting a growing food deficit for an increasing population currently estimated at 102 million [2]. As a result, food insecurity is prevalent on a large scale in Ethiopia [3], achieving national food self-sufficiency by boosting that agricultural production is a major policy concern in Ethiopia. The target is to double cereal yield, currently estimated at 2.2 t/ha compared to 3.5 t/ha in Southeast Asia and the world average of 4.0 t/ha.

Teff (*Eragrostis tef* Zucc¹) is one of the five major cereals, along with maize (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and sorghum (*Sorghum bicolor*), that provide the bulk of staple foods for the Ethiopian population [4]. The crop covers more than 3 million ha of farmland and contributes immensely to

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1 *Eragrostis tef* (Zucc) is a small cereal extensively cultivated in Ethiopia for its grain that is used to make the most favorite national food – Enjera.
national and household food security [5]. While teff grain is the most favorable staple, its straw is also a highly marketable commodity as animal feed and mud wall plastering. Despite its importance, teff yield is low with a national average of 1.2 t/ha [6]. Teff productivity is far below its potential yield, and some researchers reported from research stations and their farm verification trials [7]. Nutrient losses by soil erosion and complete removal of crop residues for animal feed and dung burning as household fuel are among the major contributing factors to the low yield, along with drought in some areas [3,7–10]. Another important limiting factor is low and unbalanced fertilizer application, with a national average of 43 kg urea and 65 kg DAP (di-ammonium phosphate) per ha [4]. Fertilizer dosage based on only N and P supply is believed to have caused nutrient imbalances in the soils. Over time the soil reserve is depleted of other nutrients, which limits the crop yield because of nutrient imbalance and uptake of other macronutrients, such as K and micronutrients (Zn, B, and Cu) [11,12]. Thus, the conclusion can be reached that the low and unbalanced fertilization must have negatively influenced teff yields, as well as fertilizer use efficiency, because macronutrients such as K are missing in the fertilizer dosage [4].

The use of K fertilizer in Ethiopian agriculture has not been a priority due to the popular misconception that Ethiopian soils are rich in K [13–15]. Based on this, K has been excluded from fertilizer formulations, which has severely affected crop yields [16]. Research evidence is accumulating to demonstrate that K deficiencies are limiting crop yields, particularly for cereals in Vertisols [17,18]. For example, of the assessed Vertisol areas in Tigray region in Northern Ethiopia, 76% of samples have been found K deficient. Similarly, the soil fertility atlas of Amhara regional state prepared by the Agricultural Transformation Agency (ATA) indicates that about 90% of the agricultural lands require K fertilization [19]. Although some of these claims are debatable and need further field verification, the existing body of information is building on the importance of K fertilization for crop production in Ethiopia.

Vertisols cover vast areas of the Ethiopian highlands estimated at 1.13 million ha (11%) of the agricultural landmass, particularly in the central and north-western highlands of Ethiopia [20]. These soils are known to be deficient in K content due to the parent materials (e.g., alluvial deposits and limestone) that are abundant in high charge smectite and vermiculite type clays that lock up K in the clay lattice [21,22]. In addition, nutrient mining through the continuous application of N and P fertilizers, along with soil erosion and leaching losses, must have contributed to the depletion of the K stocks of agricultural soils of Ethiopia [11,12,23].

Research on K fertilization in the Ethiopian highlands began in 2015 with the advent of a blend fertilizer dosage containing 7–12 kg K/ha for different soils and crops in the form of K2O [24]. However, there was no evidence whether these rates were adequate to meet the crop requirements on different soil types, particularly for teff production in Vertisols. In addition, information on the optimum level of K for teff production on specific soil types is lacking in Ethiopia. Therefore, the present study was conducted with the objective of evaluating the response of teff to the application of different levels of K fertilizers in Vertisols and in different teff growing sites in the central highlands of Ethiopia. The study explored the role of K in increasing teff yields and aimed to determine optimum levels of K fertilizer to increase nutrient uptake and teff yields on Vertisols, hence contributing to the goal of achieving food security in Ethiopia.

2 Materials and methods

2.1 Study sites

This study was conducted in four districts (Suluta, Mulo, Moretina Jiru, and Bere) in the central highlands of Ethiopia, within the geographical bounds of 8°45′N – 9°12′N latitudes and 38°45′E – 30°00′E longitude (Figure 1). The trials were set during the main rainy season (meher) of 2015. The topography is characterized by basalt plateaus accompanied by Suluta-Sendafa alluvial plains and shallow valleys, with an elevation ranging from 1,500 to 2,500 m. The long-term mean annual rainfall varies between 1,000 and 1,200 mm with average temperatures ranging between 10 and 18°C. The mean monthly rainfall during the 2015 growing season is presented in Figure 2. Vertisols are the most dominant agricultural soils along with Cambisols, Leptosols, and Nitisols [25]. Teff is the major cereal grown, along with wheat and barley grown in rotation with faba bean (Vicia faba) and field pea (Pisum sativum). Vertisols are largely planted with teff in the rainy season and chickpea and lentils during the dry season as catch crops.

2.2 Treatments and experimental design

Five levels of K fertilizer (0, 30, 60, 90, and 120 kg K2O/ha) were arranged in a randomized complete block design
(RCBD) with three replications on a plot size of 6 m × 4 m and row spacing of 20 cm. To capture site variability, three representative farm fields were selected per site giving a total of 60 on-farm field experiments over four locations. Planting dates were those preferred by farmers based on the onset of the main rainy season (July to September). Potassium chloride (KCl: 60% K₂O) was used as the source of K. A recently released teff variety, popularly known as Kuncho, was used for the experiment at a recommended seed rate of 7 kg/ha [6]. Each plot received basal application of the government-recommended zinc blend fertilizer – NPSZn: 17.7 N – 35.3 P₂O₅ + 6.5 S + 2.5 Zn at a rate of 100 kg/ha. Split application of the recommended rate of urea (100 kg/ha) was practiced with 1/3 at planting and 2/3 top dressing at the tilling stage after the first weeding. All cultural practices were the
same across plots and standard practice recommendations for teff production were followed.

**Ethical approval:** The conducted research is not related to either human or animal use.

### 2.3 Yield data and plant tissue analysis

Fields were supervised every week after planting, and at maturity, a central plot of 9 m² was hand harvested at the ground level using hand sickle to determine straw and grain yields using a sensitive balance (digital platform scale produced by Shanghai Puchun Measure Instrument Col. Ltd., China). The harvested biomass was then separated into grain yield and straw yield by manual threshing. To know the concentrations of N, P, and K in the grain and straw and hence estimate plant nutrient uptake, 10 g plant samples were collected per plot and taken to Horticoop Ethiopia soil fertility laboratory at Bishoftu, Ethiopia. The plant samples were oven dried at 65°C to constant weight, then ground, and put into 480°C for four hours using West tune SX2-5-12G Box-type resistance furnace, produced in China. Phosphorus and K concentrations in the plant biomass samples were analyzed using the dry ashing method as outlined in ref. [26], and nitrogen concentration was analyzed using the Kjeldahl methods [27].

### 2.4 Soil analysis methods

A total of 60 topsoil samples (four sites with 15 samples per site) from 0 to 20 cm depth were collected before planting to make a composite sample, representing each site, to be used for the determination of selected physical and chemical properties at the Horticoop-Ethiopia Soil Fertility Laboratory. The samples were air dried, ground to pass through a 2 mm sieve, thoroughly mixed, and readied for the physicochemical analysis. The soil texture (% sand, silt, and clay) was determined using the modified sedimentation hydrometer procedure [28]. The pH-H₂O was measured in 1:2.5 soil to solution suspension using a pH meter [29]. The Walkley and Black method was used to determine the soil organic carbon (SOC) content [30], and total nitrogen (TN) was determined using the Macro-Kjeldahl method [27]. Available phosphorus (AP) and exchangeable bases (Ca²⁺, Mg²⁺, K⁺, and Na⁺) were determined using the Mehlich-III extraction procedure [31].

### 2.5 Statistical analysis

Teff grain and straw yields and the nutrient uptake data were subjected to ANOVA using a linear model (lm) of R statistical software version 3.5.1 [32]. The total variability was then detected using the following model:

\[
T_{ij} = \mu + R_i + K_j + S_i + KS_{ij} + \varepsilon_{ij}
\]

where \(T_{ij}\) is the total variation for a given yield component, \(\mu\) is the overall mean, \(R_i\) is the \(i\)th replication, \(K_j\) is the \(j\)th K treatment effect, \(S_i\) is the site effect, \(KS_{ij}\) is the interaction between K levels and site, and \(\varepsilon_{ij}\) is the variation due to random error. Where there was a significant difference, mean separation was done using the least significant difference (LSD) test at 5% probability level.

### 3 Results

#### 3.1 Initial condition of the soils in the study area

Table 1 presents the initial soil conditions in the study sites based on samples collected before planting. As expected for Vertisols, the soils were all clay in texture, slightly acidic to neutral in reaction (pH 6.0–6.7), and moderate in AP, but very low in OC and TN. Conversely, and consistent with a high clay content, the soils were very high in CEC and exchangeable Ca and Mg, but the levels of exchangeable K were variable across sites: high at Sululta (1.22 cmol(+) /kg) and Bereh (1.02 cmol(+) /kg), but medium (0.7 cmol(+) /kg) at Moretna Jiru sites. Cation exchange capacity and exchangeable bases were very high in all sites, which was consistent with the dominance of smectitic minerals and ferromagnesian parent materials (basalt) [16].

#### 3.2 Effect of potassium fertilizer on teff grain and straw yields

The application of K fertilizer resulted in a highly significant \((p < 0.001)\) effect on teff grain and straw yield but
Table 1: Selected chemical and physical properties of the four study sites sampled in 2015 before planting from central Ethiopian highlands

| Parameters                              | Locations          |
|-----------------------------------------|--------------------|
|                                         | Mulo   | Bereh   | Moretina Jiru | Sululta |
| Sand (cmol⁺/kg)                          | 21     | 13     | 9             | 8      |
| Silt (cmol⁺/kg)                          | 20     | 21     | 10            | 12     |
| Clay (cmol⁺/kg)                          | 59     | 66     | 81            | 81     |
| Soil texture (cmol⁺/kg)                  | Clay   | Clay   | Clay          | Clay   |
| pH-H₂O (cmol⁺/kg)                        | 6.00   | 6.70   | 6.60          | 6.4    |
| OC (%)                                  | 1.53   | 0.85   | 0.73          | 1.81   |
| TN (%)                                  | 0.14   | 0.07   | 0.16          | 0.15   |
| AP (mg/kg)                              | 10     | 10     | 16            | 11     |
| CEC (cmol⁺/kg)                           | 52     | 55     | 61            | 55     |
| Exchangeable bases (cmol⁺/kg)            | 27     | 35     | 38            | 33     |
| Ca                                       | 10.95  | 10.10  | 10.00         | 10.00  |
| Mg                                       | 0.76   | 1.02   | 0.70          | 1.22   |
| K                                        | 0.15   | 0.17   | 0.13          | 0.19   |
| Na                                       | 33     | 33     | 33            | 33     |

Table 2: The effect of potassium fertilizer levels and location on teff grain and straw yields in the central highlands of Ethiopia

| Treatments | Grain yield (kg/ha) | Straw yield (kg/ha) |
|------------|---------------------|---------------------|
| K levels (kg/ha) |                     |                     |
| 0          | 1.576<sup>a</sup>  | 5.798<sup>c</sup>  |
| 30         | 1.777<sup>b</sup>  | 5.955<sup>b</sup>  |
| 60         | 1.833<sup>ab</sup> | 6.376<sup>ab</sup> |
| 90         | 1.875<sup>a</sup>  | 6.649<sup>a</sup>  |
| 120        | 1.749<sup>b</sup>  | 6.774<sup>a</sup>  |

- | F-value | 18.0751 | 9.0557 |
- | p-value | <0.001<sup>***</sup> | <0.001<sup>***</sup> |

Locations

- Bereh | 1.600<sup>b</sup> | 7.199<sup>b</sup> |
- Moretina Jiru | 2.641<sup>a</sup> | 7.794<sup>a</sup> |
- Mulo | 1.528<sup>c</sup> | 6.039<sup>c</sup> |
- Sululta | 1.280<sup>d</sup> | 4.210<sup>d</sup> |

- | F-value | 620.3860 | 156.2724 |
- | p-value | <0.001<sup>***</sup> | <0.001<sup>***</sup> |

Means within column followed by the same letter are not significantly different at 5%; ***p < 0.001, **p < 0.01, *p < 0.05.

widely varied across locations (Table 2). There was a consistent increase in the teff grain yield until it reached the highest (1,875 kg/ha) at 90 kg K₂O/ha and then declined while the straw yield continued to increase. That is, the highest K-level (120 kg K₂O/ha) depressed the teff grain yield but resulted in the highest straw yield (6,774 kg/ha) (Figure 3). The inverse relation between straw and grain yield at higher levels of K application is associated with the problem of lodging. When a teff plant grows taller and produces large biomass, a weak stem cannot support it and lodging occurs.

When averaged across locations, there was a significant (p < 0.001) teff grain and straw yield difference among locations (Table 2). The highest teff grain (2,641 kg/ha) and straw (7,794 kg/ha) yields were obtained at Moretina Jiru, while the lowest grain (1,280 kg/ha) and straw (4,210 kg/ha) yields were at Sululta (Table 2). This was likely due to the differences in soil and climate conditions between the study sites. As presented in Table 1, soils in Moretina Jiru are very low in exchangeable K, TN, and AP, and hence, response to applied K was highest there. In addition, climatic conditions, particularly the distribution of the rainfall during the growing season, were more favorable at Moretina Jiru, resulting in a better yield response to applied fertilizer. Conversely, at Mulo and Sululta, although N and P were sufficient in the soil, the poor rainfall distribution resulted in low teff yield response (Figure 3).

Location by treatment interaction effect also showed a pattern of strong variability across locations (Figure 4). Yield response was highest in sites, where N supply was sufficient, K was deficient, and rainfall amount and distribution were favorable, such as in Moretina Jiru where the application of 60 kg K₂O/ha gave the highest grain yield. There was a considerable yield decline at higher and lower application rates at Moretina Jiru, while all levels of K fertilizer actually depressed the teff yield at Sululta sites. At Bereh and Sululta, there was no statistical difference between the control plots and plots treated with different rates of K, except the one treated with 90 kg K₂O/ha (Figure 4). The soil conditions at Mulo were similar to that of Moretina Jiru (soil sufficient in N and deficient in K) where good yield response to K fertilizer was expected but low rainfall and poor distribution during the growing season resulted in low yields. The application of K₂O at a rate of 60 kg/ha resulted in a high yield at Moretina Jiru and Mulo sites. However, the application of K₂O at a rate of 90 kg/ha resulted in high teff grain yield at Sululta and Bereh.

3.3 Effect of potassium fertilizer on nutrient uptake

Averaged over location, the application of K significantly (p < 0.05) affected N and P uptake but had no significant effect on K itself uptake (Table 3). The highest mean N (131 kg/ha), P (24 kg/ha), and K (45 kg/ha) uptake was achieved by the application of 90 kg K₂O/ha, and the
lowest was from the control plots (Table 3). This is consistent with the highest grain and straw yield that was achieved at 90 kg K₂O/ha, suggesting a positive correlation between K uptake and teff yield. It is important to note that increasing levels of K increased the uptake of N and P but not K, suggesting the strong nutrient interaction effect.

### 3.4 Teff agronomic efficiency for the K applied in Vertisols

The highest agronomic efficiency (13.3 kg/kg) for the applied K was recorded at Mulo with the application of 30 kg K₂O/ha, and the lowest agronomic efficiency (0.04 kg/kg) was recorded at Sululta with the application
of 120 kg K₂O/ha. At Moretena Jiru, lower rates of K resulted in high agronomic efficiencies and the agronomic efficiency declined as the application rate increased. Generally, a low rate of K fertilizer application resulted in high K agronomic efficiency at Mulo and Moretena Jiru. At Suluta, the agronomic efficiency of K increased with increased K. On the contrary, variable trends were observed for the different K ranges applied at Bereh (Figure 5).

### 4 Discussion

Our results showed that the application of K fertilizer resulted in higher teff grain and straw yields, but this varied strongly across locations. This is in line with the findings of Misskire et al. [33], who reported improved teff yield and nutrient uptake as a result of K fertilization in Gojam, North-Western Ethiopia. These findings demonstrate the importance of balanced nutrition of N, P, and K as the application of one of these nutrients may accentuate the uptake and depletion of the others, and conversely, the absence of any of these elements may depress yields and nutrient use efficiency [34]. The findings are remarkable as K fertilization has received little attention in Ethiopian agriculture based on the popular misconception that Ethiopian soils are rich in K [35,36]. This finding corroborates the finding of others. For example, Demiss et al. [37] reported that K fertilizer application significantly affected teff grain and straw yield in 67% of the researched 18 locations in central Ethiopia.

The significant locational differences observed in this study emphasizes the importance of soil and site-specific fertilizer recommendation. This is because Vertisols in Ethiopia are too diverse in their chemical properties as the alluvial and colluvium deposits vary in their mineralogy and chemical properties [38,39]. In addition, the availability of fertilizer K to crops depends on the fraction of K already available in the soil and the type and amount of clay minerals available in the soil system [40]. Differences in soil properties that most dictated crop response to K fertilizer include the level of deficiency or availability of K in the soil for plant uptake, the soil pH (that regulates nutrient availability), and the status of organic matter (that regulates a range of soil physical and chemical properties including retention of nutrients). Applied K did not give a significant yield response in sites, where K levels

| Treatments | N (kg/ha) | P (kg/ha) | K (kg/ha) | F-value | P-value |
|------------|-----------|-----------|-----------|---------|---------|
| K levels   |           |           |           |         |         |
| 0          | 91³        | 13³       | 36³       | 2.923   | 0.03*   |
| 30         | 130³       | 21³       | 36³       | 2.727   | 0.04*   |
| 60         | 94³        | 15³       | 33³       | 1.159   | 0.13ns  |
| 90         | 131³       | 24³       | 45³       |         |         |
| 120        | 109³       | 17³       | 44.7³     |         |         |
| P-value    | 0.03*      | 0.04*     | 0.13ns    |         |         |

Means within column followed by the same letter are not significantly different at 5%; ***p < 0.001, **p < 0.01, *p < 0.05, ns – non-significant.

Figure 5: Agronomic efficiency of K application for the teff grain yield.
were sufficient (Mulo and Sululta). This indicates that crops respond to external fertilizer nutrient application only when the soil is deficient in that nutrient, as confirmed by previous studies [41]. Strong teff yield response to K-fertilizer was observed in sites where the soil is sufficient in N and deficient in K (e.g., in Moretina Jiru – Table 1), in addition to good amounts and favorable distribution of rainfall. Crop response to applied fertilizer may be expected only when the soil is deficient (or below critical level) in that nutrient for crop uptake [42]. There was strong nutrient interaction, particularly between N and K, in the soil and those externally supplied through fertilizer application, which is consistent with the mainstream literature [41]. On the other hand, the low straw and grain yield in the control plots could be the result of nutrient imbalance among N, P, and K uptake [37].

There is a fertilizer use increase in Ethiopia, but the teff yield increase was not observed following the increase in the fertilizer use [43]. One contributing factor could be the poor uptake of nutrients applied to the soil, which otherwise could be a loss to the environment resulting in an economic loss to the farmer. According to Gebrekidan et al. [44], the nutrient uptake was high in plots treated with blend fertilizers containing K compared to the plots treated with DAP and urea alone. A more comprehensive study covering 83 farm fields in the three big producers of teff in Amhara, Tigray, and Oromia regions showed a significant yield increase following the use of K-containing blends compared to the conventional teff production common to Ethiopian farmers [10]. This high yield could be because of a balanced uptake of the necessary plant growth nutrients in the soil system. Being a useful measure of the nutrient use efficiency, agronomic efficiency quantifies the total economic output as a result of all the nutrient used in the production [45]. This study reviled that agronomic efficiencies of N and P increased as a result of the increased K application to teff.

The site- and soil-specific crop response observed in experimental results also highlight the interaction effect of nutrient supply from fertilizer and moisture on crop yields. It further substantiates farmers’ argument that fertilizer application alone cannot improve yields without sufficient amounts and good moisture distribution during the growing season. As an Ethiopian farmer says, “Fertilizer without moisture is no better than a stone or sand in the field” [46]. Scientific studies confirm farmers’ observations that adequate soil moisture enhances the efficiency of applied fertilizer and nutrient uptake, and there is a strong interaction between applied fertilizer and soil moisture in crop yield determination [47].

5 Conclusion

This study examined the response of teff crop to different rates of K fertilizer on Vertisols in different contrasting sites in the central highlands of Ethiopia. In spite of the long held view that Ethiopian soils are rich in K, and its inclusion in the cereal fertilization program is not needed, in this research we found locations and sites in the central highlands where K-deficiency limits the teff production (e.g., Moretina Jiru, Mulo). The supply of K significantly improved nutrient uptake, agronomic efficiency, and ultimately teff grain and straw yields in the sites, where K soil stock was low and rainfall distribution was adequate (e.g., Moretina Jiru and Mulo). In these sites, the application of 90 kg K2O5 gave the highest yield return and should be extended to farmers along with the extension recommendation (100 kg/ha NPSZnB). In other sites, namely, Suluta and Bereh, the soil K stock is rather high and rainfall distribution is poor; therefore, return to K fertilizer is not attractive. Such a nuanced, soil- and site-specific fertilizer approach is vitally important for countries like Ethiopia where diversities in soil properties and climatic conditions dictate the response to fertilizer application and ultimate impact on national food security.

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Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.
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