



Research Article

Potassium critical level in soil for Teff (*Eragrostis tef* (Zucc.) Trotter) grown in the central highland soils of Ethiopia

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Abstract

Responses to potassium (K) fertilizer are reported in different parts of Ethiopia in recent years, contrary to the general perception that K fertilizer was not necessary on the soils. However, use of adequate K level for maximum economic yield is possible only when soil test data are calibrated against response curve for a given crop and soil type. This pot trial was conducted to calibrate K soil test with the response of teff (*Eragrostis tef* (Zucc.)) at application of increasing levels of K. Random soil samples (0–20 cm) were collected from 60 locations having Mehlich-3 (M-3) K soil test values ranging from 16 to 910 mg kg⁻¹ across 20 teff growing districts in the highlands of Ethiopia. The relative biomass yield of teff was significantly correlated with Mehlich-3 extractable K, suggesting that the extraction method fairly estimated the available soil K. Soil test M-3 extractable K values were categorized, based on relative biomass yield, as “very low” (< 55 mg kg⁻¹), “low” (55–210 mg kg⁻¹), “medium” (210–280 mg kg⁻¹), “high” (280–500 mg kg⁻¹) and “very high” (> 500 mg kg⁻¹). And K application rates of 139 and 54 kg ha⁻¹ for the very low and low K categories respectively would suffice for optimum teff yield. The critical limit of K in soil (M-3) using the graphical method was 210 mg kg⁻¹ for the 85% relative biomass yield level. An inverse relation of yield response to the soil K status was observed suggesting that application of K fertilizer increases yield of teff in low status soils. However, field verification is required to draw sound conclusions.

Keywords Optimum yield · Response · Calibration · Soil test levels

Abbreviations

| | |
|----------|------------------------------------|
| K | Potassium |
| M-3 | Mehlich-3 |
| EthioSIS | Ethiopian soils information system |
| GPS | Global positioning system |
| ICP | Inductive couple plasma |
| LSD | Least significant difference |

1 Introduction

Potassium (K) deficiency has not been recognized as a problem in Ethiopia and until recently a universal belief “potassium fertilizers are not necessary” was adopted by

many researchers. However, the Ethiopian Soils Information System (EthioSIS) project conducted a soil fertility survey in the farm lands of the country and published a soil fertility status and fertilizer type recommendation atlas that indicated presence of a highly negative K balance and deficiency in different locations [1, 2]. Besides, reports indicated K deficiencies in Ethiopian soils [3] and sharp increases in crop yields as a result of addition of potassium—wheat and teff [4], wheat [5] and potato [6]. However, little or no emphasis is given at national or regional level on the effect of K fertilization, soil K balance or determination of K critical level in the fertilization program of the country.

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Teff (*Eragrostis tef* Zucc. Trotter) is a major cereal crop indigenous to Ethiopia [7] and is a major food grain, mainly used to make *injera*, a traditional fermented, soft porous thin pancake with a sour taste [8, 9]. Depending on variety and altitude, teff requires 90 to 130 days for growth [10]. Teff was first (24%) in area coverage and second in production (17.29%) in 2016/17 cropping season. An area of 3.02 million hectares was cultivated and yielded 5.02 million metric tons [11].

Soil and plant analyses are commonly performed to assess the fertility status of a soil and have often been used as an effective approach to distinguish nutrient status in field crops [12]. The analyses determine the nutrient requirements of crops, while plant analysis is used for establishing the nutrient sufficiency under well-defined conditions of experimentation and collection of soil and plant samples. However, the analytical results do not indicate the most limiting nutrient according to Liebig's law of the minimum. Critical soil and plant nutrient deficiency values have to be determined to separate the responsive from the non-responsive soils and to efficient use of the fertilizer [13]. Critical deficiency level of nutrients varies for different soils, crops, and environments [12, 14].

Potassium is a basic nutrient for plant and animal life and plays many essential roles in plant nutrition and metabolism, is required in large amounts by most crops. Potassium plays a remarkable role in transpiration, stomatal opening and closing and osmoregulation [15]. It interacts with many other plant constituents to affect crop yield and quality [16]. Potassium is an essential element that is mandatory for all plants' growth [17]. Potassium is taken up in large quantities by plants, is highly mobile within plant vascular systems and plays an essential role in a number of metabolic functions. Over 60 enzymes require K for catalytic activity, some of which play a role in protein synthesis and sugar degradation [18]. Besides, it promotes the transportation of assimilates, control of stomata opening, enzyme activation in plants especially those responsible for energy transfer and formation of sugars, starch and protein as well as promotion of microbial activities and the nutrition and health of man and livestock [19].

Research findings reported critical limits of available K in different crops in different locations outside Ethiopia, viz-a-viz, 165 mg kg⁻¹ [20], 68 mg kg⁻¹ in Tennessee, USA [21] and 132.9 mg kg⁻¹ in Uruguay [22]. The EthioSIS project also developed a literature based, and blanket, critical levels of nutrients for the different cereal crops such as maize, wheat, teff and barley. However, information pertaining to the critical limits of K on teff in Ethiopia is lacking. This study was therefore conducted to determine the soil critical levels of K for teff and provide information on the need for K fertilization in different K status soils of Ethiopia.

2 Methodology

2.1 Description of experimental area and sampling locations

A pot experiment was conducted using teff (*Eragrostis tef*, variety- Quncho) as test crop in a lath house in the period between October 2015 and February 2016 at the Debre Zeit Agricultural Research Center (08° 46'10.10"N and 38°59'56.13"E) and an altitude of 1889 meters above sea level. Quncho is selected as test variety as it is the first popular teff variety in Ethiopia and is considered as suitable variety for most teff growing regions. Sixty surface representative soil samples were collected in 2015 from across 20 teff growing districts of Ethiopia (Fig. 1) to be used as test soils in this experiment. The soils were collected from areas identified as low (< 190 mg kg⁻¹), medium (190–600 mg kg⁻¹), and high (600–900 mg kg⁻¹), based on their available K status by the national soil fertility status atlas [1]. Global Positioning System (GPS) was used to identify the geographical locations of each sampling point.

2.2 Soil and plant sampling

Each soil sample was obtained by composing 10–12 random cores from the top 20 cm. The soils vary in available K, pH and texture. The samples were mixed, air-dried, and passed through 1 cm sieve to remove gravel and debris and prepared for pot trials. A portion of the sample was ground and sieved through a 2 mm sieve for physical and chemical analyses. With regard to plant samples, the above ground biomass was harvested after 100 days of emergence and weighed. The teff plant samples were washed with distilled water to remove the dust and soil particles from the samples. The plant samples were kept in paper bags and then dried in a greenhouse to constant weight. The dried samples were weighed for their dry matter yield.

2.3 Soil and plant analysis

The particle size distribution was done by the HORIBA-Partica (LA-950V2) laser scattering particle size distribution analyzer [23] and LA-950 software version 7.01 for Windows [24]. Soil pH and electrical conductivity (EC) were measured using 1:2.5 soil: water ratios. Exchangeable K, Ca, and Mg and available P, Sulfate-S and extractable Zn were extracted following Mehlich-3 (M-3) procedure [25]. Organic carbon was predicted from mid infrared spectra of soil samples. Plant samples were dried at 65 °C and the dried plant samples were powdered in a warring

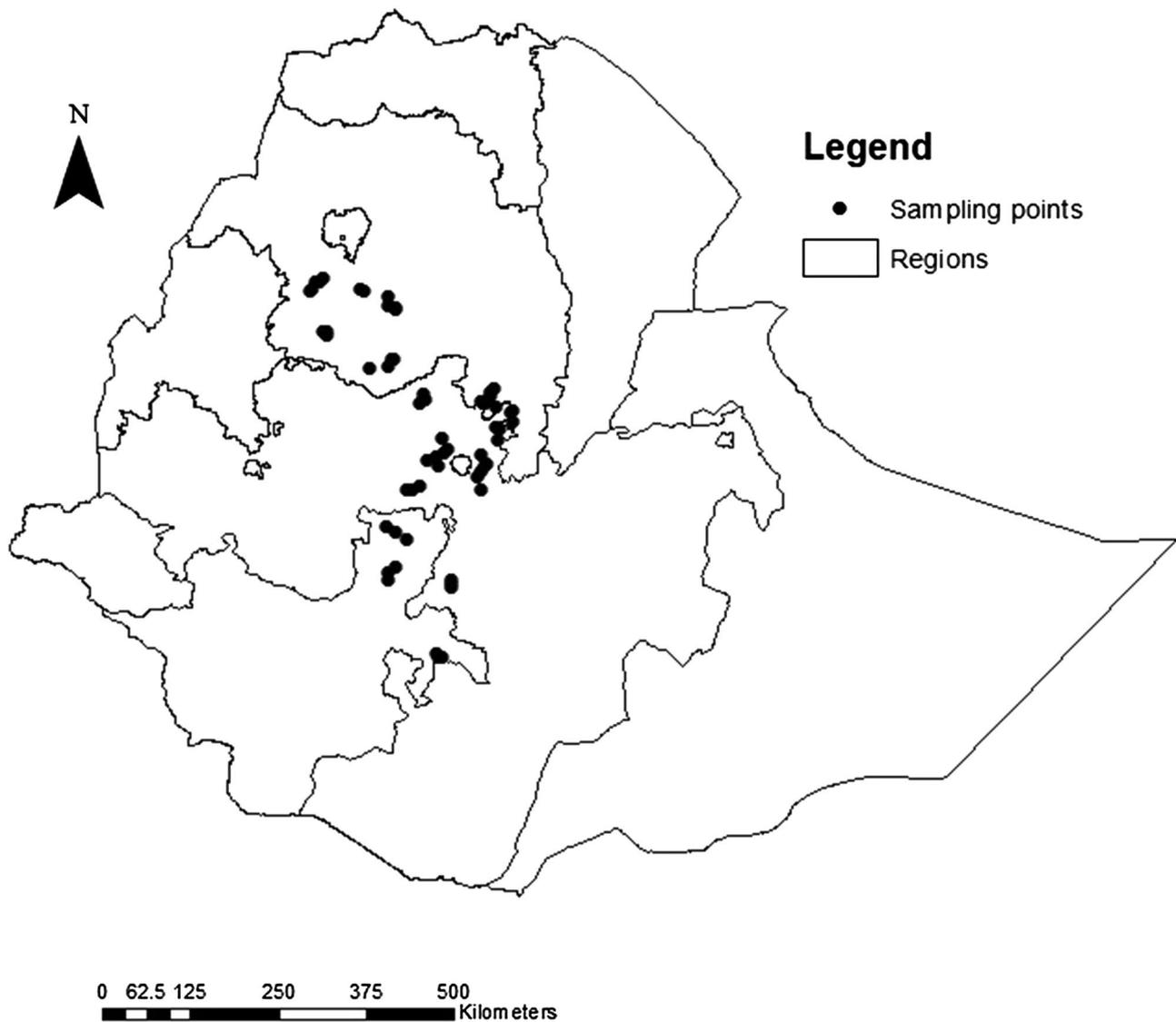


Fig. 1 The sampling points (60) in 20 districts

stainless-steel grinder. Dry powdered plant samples were ashed in a muffle furnace at 500 °C and the ash was extracted in 10 ml of 6 M HCl and dried on hot plate for 15 min at 140 °C. The ash was dissolved in 10 ml of 1 M HCl and K content in filtrate was analyzed with an Inductive Couple Plasma (ICP).

2.4 Experimental design, treatments and management practices

The pot trial was conducted by using a total of 3 kg of the dried soil sample in a plastic pot having 16 cm top and 14 cm bottom diameters. Four levels of potassium: 0, 60, 120 and 180 kg ha⁻¹ K, were applied as potassium chloride (60% K₂O) replicated three times in a completely

randomized design. There were thus 12 pots per soil and a total of 720 experimental pots. To ensure that K was the only nutrient element limiting teff production, optimum and uniform doses of N, P, S and Zn were applied at the rates of 120, 60, 15 and 3 kg ha⁻¹ respectively, as NPSZn compound fertilizer (12-45-0 + 5S + 1Zn). Of the nutrients supplied, 100% of P, K, S and Zn and 30% of N were applied as basal fertilizers before planting while 70% of N was applied as urea 30 days after planting to all pots. All the nutrients were applied as solution. The pots were watered to saturation level and allowed to drain to the field capacity. At field capacity, about 20 uniform seeds were sown in each pot and the seedlings were thinned to maintain 12 plants per pot a week after emergence. Soil moisture was maintained nearly at field capacity throughout the growing period. Watering and intercultural operations

like weeds control and plant protection measures were employed uniformly in each pot as and when required.

2.5 Data collection

Data on above ground dry matter (AGDM) and total nutrient concentration was collected from each pot. Bray's percent yield and yield response were calculated using the following formula:

Bray's percent yield = (AGDM yield at 0 K/AGDM yield at optimum K) × 100

$$\% \text{ response at } T_x \text{ kg K ha}^{-1} = \frac{\text{Yield at } T_x \text{ kg K ha}^{-1} - \text{yield at } 0 \text{ kg K ha}^{-1}}{\text{Yield at } T_x \text{ kg K ha}^{-1}} \times 100$$

where T_x refers to treatment at "x" K rate.

2.6 Determination of K requirement factor (Kf)

Potassium requirement factor (Kf) is the amount of K in kg needed to raise the soil K by 1 mg kg⁻¹. It enables to determine the quantity of K required to raise the soil test by 1 mg kg⁻¹, and to determine the amount of fertilizer required per hectare to bring the level of available K above the critical level [26].

It was calculated using available K values in samples collected from unfertilized and fertilized plots. Potassium requirement factor was expressed as:

$$Kf = \text{kg K applied} / \Delta \text{ soil K}$$

where Δ soil K refers to the difference in soil available K between before planting and after harvest.

The rate of potash fertilizer to be applied (Ka) was expressed in terms of critical K concentration (Kc), initial soil K value (Ki) and K requirement factor (Kf) for the different K status soils as:

$$Ka = (Kc - Ki) \times Kf$$

2.7 Determination of the critical level

The critical level is a soil test level that indicates the division between responsive and non-responsive conditions to potassium application. Figure 3 shows the graphical representation of relative biomass yield and soil test K in the form of XY scattered graph points. For the determination of critical value of K, soil test values were plotted on X-axis and Bray's per cent yield values on Y-axis. The points obtained from relative biomass yield percentage and available K are divided into four quadrants by

drawing parallel lines to 'X' and 'Y' axes in such a way that the maximum scattered points are in the two opposite quadrants (1 and 3). The point where the line intersects the 'X' axis is defined as critical limit of soil.

2.8 Statistical analysis

Data were analyzed by analysis of variance, and regression analysis was performed wherever necessary using

SAS software version 9.2 [27] and excel. An appropriate regression model was selected based on the highest R². The difference between treatments was determined using the least significant difference (LSD) test at the 0.05 probability level. The critical limits of potassium in soil was determined graphically by plotting percentage yield against soil available K using the procedure of [28].

3 Results and discussion

3.1 Physico-chemical properties of the soils

The physicochemical analyses of the experimental soils revealed that soil texture varied from sandy clay loam to clay, whereby the mean values of clay and silt contents in different categories varies from 40 to 54% and 23–31% respectively (Table 1). The soil pH values ranged from 4.7 to 8.1 with a mean of 6.2 indicating the soils are mostly acidic in reactions. Some of the tested soils had pH < 5.5 showing the characteristics of a highly weathered tropical soil. In accordance with the ratings of [2], the available P ranged from very low to low, exchangeable K from very low to very high, S and Zn from low to medium (Table 1). The data also showed that the experimental soils were variable not only in their K status but also in other physical and chemical parameters.

In contrast to [2] and other critical levels obtained somewhere, the present findings resulted in a different critical levels of K, whereby the soils of the study area were categorized as "very low" (< 55 mg kg⁻¹), "low" (55–210 mg kg⁻¹), "medium" (210–280 mg kg⁻¹), "high" (280–500 mg kg⁻¹) and "very high" (> 500 mg kg⁻¹).

The percentage of soils categorized as very low, low, medium, high and very high in their M-3 K contents were 10, 53, 14, 18 and 5% respectively (Table 2). EthioSIS

Table 1 Selected physico-chemical properties of the experimental soils collected from 60 locations

| K Status category (mg kg ⁻¹) | Values | Soil parameters | | | | | | | | | | |
|--|--------|-----------------|------|----|------------|--------------------------------|--|----------------|-----------------|-----------------|-----------|----------------|
| | | Clay | Silt | OC | pH (1:2.5) | Ec (dS m ⁻¹) (1:5) | Available P (mg kg ⁻¹)-Mehlich-3 | Exchangeable K | Exchangeable Ca | Exchangeable Mg | Sulfate S | Extractable Zn |
| Very low | Max | 58 | 33 | 4 | 8 | 2 | 6 | 56 | 4880 | 1510 | 26 | 8 |
| | Min | 31 | 27 | 1 | 5 | 0 | 1 | 16 | 1430 | 196 | 10 | 0 |
| | mean | 41 | 29 | 2 | 6 | 1 | 3 | 37 | 2135 | 509 | 14 | 3 |
| | Range | 27 | 5 | 3 | 3 | 1 | 5 | 40 | 3450 | 1314 | 15 | 8 |
| Low | Max | 83 | 45 | 4 | 7 | 6 | 15 | 210 | 8370 | 1580 | 21 | 11 |
| | Min | 33 | 9 | 1 | 5 | 0 | 1 | 63 | 1010 | 130 | 10 | 1 |
| | mean | 54 | 27 | 2 | 6 | 1 | 4 | 147 | 3165 | 665 | 12 | 2 |
| | Range | 51 | 36 | 3 | 3 | 6 | 14 | 147 | 7360 | 1450 | 10 | 10 |
| Medium | Max | 82 | 44 | 3 | 7 | 2 | 12 | 279 | 6070 | 1220 | 22 | 6 |
| | Min | 29 | 11 | 1 | 6 | 0 | 1 | 211 | 880 | 120 | 10 | 1 |
| | mean | 54 | 28 | 2 | 6 | 1 | 4 | 236 | 2596 | 499 | 15 | 3 |
| | Range | 53 | 34 | 2 | 1 | 2 | 10 | 68 | 5190 | 1100 | 12 | 5 |
| High | Max | 80 | 38 | 4 | 8 | 1 | 26 | 498 | 16,600 | 1310 | 19 | 4 |
| | Min | 25 | 11 | 1 | 5 | 0 | 1 | 238 | 880 | 120 | 10 | 1 |
| | mean | 54 | 23 | 2 | 7 | 0 | 5 | 350 | 6866 | 699 | 12 | 2 |
| | Range | 55 | 27 | 3 | 3 | 0 | 25 | 260 | 15,720 | 1190 | 8 | 3 |
| Very high | Max | 61 | 40 | 2 | 8 | 1 | 22 | 646 | 5040 | 962 | 78 | 7 |
| | Min | 27 | 18 | 1 | 8 | 0 | 3 | 533 | 4310 | 374 | 10 | 1 |
| | mean | 40 | 31 | 1 | 8 | 1 | 14 | 578 | 4747 | 583 | 34 | 4 |
| | Range | 34 | 22 | 1 | 0 | 1 | 19 | 113 | 730 | 588 | 67 | 6 |

categorized M-3 K contents < 90 mg kg⁻¹ as very low, 90–190 mg kg⁻¹ as low, 190–600 mg kg⁻¹ as medium, 600–900 mg kg⁻¹ as high and > 900 mg kg⁻¹ as very high regardless of crops. Based on our findings however, the medium range under EthioSIS categorization was found to be too wide and grouped under high and very high category for teff. The present results showed the need for categorizing the available K status of the soils for different crops in Ethiopia.

Monitoring of soil after crop harvesting showed (data not shown) that there was a buildup of K in soil with the application of potassium and K concentration in soil was increased in the same fashion as the K application rate was increased.

3.2 Plant K concentration

Application of potassium significantly increased the K concentration of the teff biomass (Table 3). A mean K concentration of 1.32% was recorded in the plants treated with 120 kg K ha⁻¹ while 0.97% K was obtained from treatments without K application. The sufficiency ranges for K in leaves are 1.80 to 2.6% [29] for mature rice; 2.5 to 3.5% and 1.5–3.0% for maize and wheat whole

tops respectively [30]. The K concentration had significant ($p < 0.001$) correlation both with K levels (rates) and interaction between K levels (rates) and soil K status (Table 3) indicating that teff K uptake from applied fertilizer depends on the initial soil K status. Potassium concentrations in the tissue significantly ($P < 0.001$) increased with increasing K rate till 120 kg ha⁻¹ (Fig. 2, Table 3). These increases were generally more pronounced in low K test soils as compared to those soils with high K test (Fig. 3) and are similar to reports by [31, 32].

The K concentration of the teff biomass in all treatments fall below the optimum range in accordance with [29], who reported optimum tissue K levels varying from 1.8 to 2.6%. This is probably because the samples were collected at harvesting stage where the K concentration decreases as growing season advances [33].

3.3 Classification of soil critical levels

The points from relative biomass yield percentage and soil K concentration are scattered in two positive quadrants (Fig. 3). When separated by 85% yield horizontal line, the available K level of 210 mg kg⁻¹ was detected as critical

Table 2 Potassium soil test categories and potassium rate required to raise the soil K to critical level determined for teff

| No | Soil test category | Relative biomass yield (%) | K level (mg kg ⁻¹) | Soils category (%) | Rate of potash fertilizer to be applied (kg ha ⁻¹) |
|----|--------------------|----------------------------|--------------------------------|--------------------|--|
| 1 | Very low | < 65 | < 55 | 10 | 139 |
| 2 | Low | 65–85 | 55–210 | 53 | 54 |
| 3 | Medium | 85–90 | 210–280 | 14 | 0 |
| 4 | High | 90–95 | 280–500 | 18 | 0 |
| 5 | Very high | > 95 | > 500 | 5 | 0 |

Table 3 Teff response to potassium application

| Factors | Total biomass (kg m ⁻²) | Plant height (cm) | Panicle length (cm) | Plant K concentration (%) |
|-----------------------------|-------------------------------------|-------------------|---------------------|---------------------------|
| 0 (kg ha ⁻¹ K) | 1.35d | 69.83c | 21.68c | 0.968c |
| 60 (kg ha ⁻¹ K) | 1.50b | 74.67b | 23.00ab | 1.212b |
| 120 (kg ha ⁻¹ K) | 1.60a | 77.06a | 23.76a | 1.319a |
| 180 (kg ha ⁻¹ K) | 1.43c | 71.37c | 22.41bc | 1.214b |
| M-3 Soil test K | *** | *** | *** | *** |
| K levels | *** | *** | *** | *** |
| K level × soil test K | ** | *** | *** | *** |
| CV (%) | 15.27 | 11.31 | 21.67 | 10.98 |
| LSD (0.05) | 0.0465 | 1.72 | 1.02 | 0.0268 |

LSD least significant difference, CV coefficient of variations

Significant at ** $P \leq 0.01$, *** $P \leq 0.001$

Means followed by same letter(s) within a column do not differ at $P \leq 0.05$

values of K in soils for teff. A positive and significant correlation (logarithmic, $R^2 = 0.90$) was also found between available K and Bray's percentage yield (Fig. 3).

The purpose of soil test critical levels is to describe soil test results in easily understandable terminology and to simplify the process of making fertilizer recommendations by placing soils in response categories [34]. These critical levels can provide estimates of the probability of response to fertilization [35]. The K requirement factor was calculated for each soil category.

The five soil K status categories differed in their K requirement to reach sufficiency. Soils in the categories of medium, high and very high tests could produce 85–90, 90–95 and above 95% relative biomass yield without external K supply (Table 2). On the other hand, the low K status (55–210 mg kg⁻¹) soils require application of 54 kg ha⁻¹ K to achieve 65–85% relative biomass yield while 139 kg ha⁻¹ K is required in the very low K status soils. The results suggest that K application is crucial for growing teff when the extractable soil K is below the threshold value of 210 mg K kg⁻¹ and this K critical level can be used for the tested soil to predict teff yield response to K fertilization.

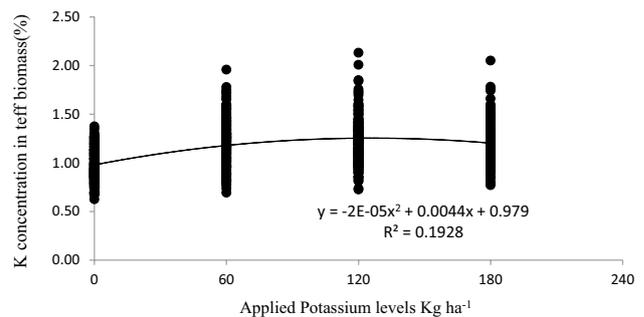


Fig. 2 Effect of potassium application on plant K concentration of teff whole tops

3.4 Yield response to K application

The results of the pot trials revealed that the biomass of the plants without K treatment was significantly ($p < 0.001$) less than those treated with K in all soils (Table 3). Application of K increased the dry matter yield in almost all soils, the highest response being in low K status soils followed by medium and high K status soils (Fig. 4). The findings

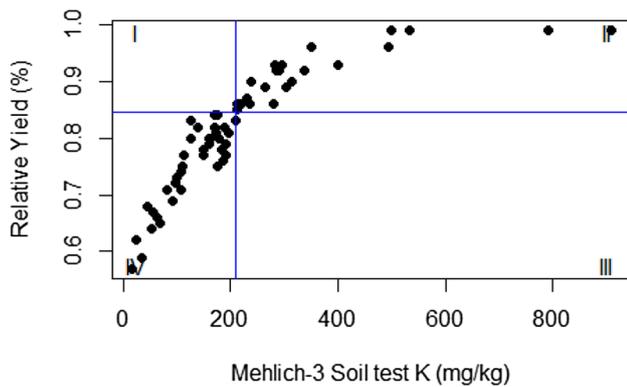


Fig. 3 Critical level of potassium in soils for teff (Cate and Nelson Method)

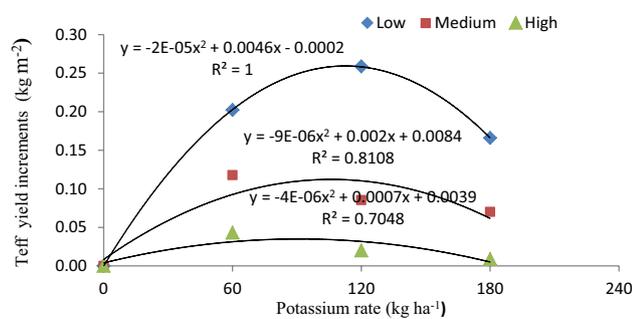


Fig. 4 Average yield response of teff to increasing levels of K application in different K status soils

were in line with the results of [36] on wheat and maize, [37] on sorghum and [38] on rapeseed, which indicated higher response to K in soils with low K status and low response in high K status soils.

However, higher dry matter yields were obtained from medium and high K status soils as compared to the low K status soils that might be due to the better inherent qualities of the soils with medium and high K contents. The highest dry matter yields were obtained at applications of 120 kg ha⁻¹ K on almost all soils followed by 60 kg ha⁻¹ K, and significant differences were observed between treatments with K application (+K) and the treatment without K application (-K) treatments and among K levels (Table 3) indicating that K was a limiting nutrient for teff in the selected low K status soils for teff. The study concluded that a response to K fertilization is likely when the M-3K value is at low and very low status and decreases when the value exceeds the critical level (Fig. 3).

Plant height and panicle length also showed similar trends with biomass yield. Like biomass yield, the highest plant height and panicle length was recorded at 120 kg K ha⁻¹ followed by 60 kg K ha⁻¹ application and were significantly ($p \leq 0.001$) higher than the control (Table 3). The

interaction between K levels and soil test K significantly ($p \leq 0.001$) affected aboveground biomass, plant height and panicle length (Table 3) indicating that soils vary in their K fertilizer requirement due to their K status as well as their inherent soil quality parameters.

4 Conclusion

The critical limits generated are expected to play an important role in decision making at farm level planning, particularly for the application of balanced nutrient to ensure the yield potential of teff. Our experiment, conducted on soils collected from 60 locations, showed both soil K status and increasing levels of K application significantly influenced teff yield. The findings indicated that about 80% of the tested teff-growing fields in the Ethiopian highlands significantly responded to K application and 63% were deficient in potassium.

Yield response varied from 1 to 83%, the average being 26%. The soil extractable M-3 K status and yield response to applied K correlated inversely ($R^2 = 0.70$ to 1), whereas plant K concentration and relative biomass yield were positively correlated ($R^2 = 0.90$) with soil K. Mehlich 3-extractable soil K in post-harvest soil samples increased linearly with increasing K fertilizer rate (data not shown). The significant interaction between soil test K and applied K levels indicate the need for developing specific K rate recommendations based on soil tests. Based on the relative biomass yield of 85%, 210 mg K kg⁻¹ was recommended as critical value of K in the soils. It is therefore recommended that K application needs to be considered in the fertilizer program of Ethiopia for soils with K status below the critical level and those showing response to K application. However, due to diversified nature of soils, it is not possible to establish a fixed value of the critical limit for the available K in different soils due to changing scenarios by intensive cropping with high yielding varieties. Therefore, field experimentation should be carried out to define and refine these critical limits with reference to growing environment to verify the effect of potassium on yield to draw sound conclusions. Field trials with different rates of K fertilizer application, using different varieties and at different soil types are required so that fertilizer recommendations can be made depending on different K soil test levels and yield goals.

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Authors' contributions Mulugeta Demiss collected, analyzed and interpreted the data. Tekalign Mamo, Sheleme Beyene and

Selamyihun Kidanu helped to draft the manuscript and all authors read and approved the final manuscript.

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Availability of data and materials We declare that the data and materials presented in this manuscript can be made available as per the editorial policy of the journal.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Consent for publication All data and information are generated and organized by the authors.

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