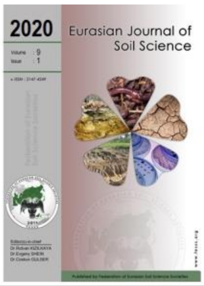
Eurasian J Soil Sci 2020, 9 (2) 105 - 118

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Effect of potassium levels on teff (*Eragrostis tef (Zucc.) Trotter*) growth and yield in Central Highland Vertisols of Ethiopia

Mulugeta Demiss [a,b,*], Tekalign Mamo [a], Sheleme Beyene [b], Selamyihun Kidanu [c]

[a] Agricultural Transformation Agency (ATA), Addis Ababa, Ethiopia
[b] Hawassa University, College of Agriculture, Pox 05. Hawassa Ethiopia
[c] OCP Societe Anonyme, Commercial Representative Office. Addis Ababa, Ethiopia

Abstract

Nutrient depletion and imbalance are among the major attributes that contribute to declining soil productivity in the highlands of Ethiopia. The blanket fertilizer recommendation, which considered only urea and Di-ammonium phosphate (DAP), was used over the past four decades to improve soil fertility for enhancing crop production. Nevertheless, the average national yields of small cereal including teff were low, despite application of nitrogen and phosphorus (NP) fertilizers. On-farm trials were conducted in the 2015/16 and 2016/17 cropping seasons at 18 locations on Ethiopian highland Vertisols to determine the response of teff to potassium (K) fertilization along with other limiting nutrients. Five K levels (0, 30, 60, 90 and 120 kg ha^{-1}) in the form of murate of potash (KCl) were used in randomized complete block design with three replications. Separate analysis of variance was conducted for each sites and year. Least Significant Difference (LSD) test at $P \leq 0.05$ was used to separate means whenever there were significant differences. Analysis of variance revealed a highly significant difference ($P < 0.01$) between treatments in both straw and grain yields and tissue nitrogen (N) and K concentrations of teff over the two-cropping seasons in 67% of the test locations. Additionally, responses to K were obtained on soils with available K test ranging between 166 and 282 mg kg^{-1}. The Ca: K and Mg: K ratios were strongly and negatively correlated with relative yield and the correlations suggest that soil with Ca: K > 50:1 and Mg: K >15:1 are likely to respond to potassium fertilization. The yield advantage accrued due to K application ranged from 30 to 77% in 2015/16 and 8 to 51% in 2016/17 seasons. The economic optimum K fertilizer application rates varied between 60 kg K ha^{-1} in 44% of the sites to 90 kg K ha^{-1} in 23% of the sites. The findings highlighted the need for revisiting fertilizer program to enhance the yield and nutrient uptake of teff in K responsive soils and developing critical levels for K in the study sites.

Article Info
Received : 19.02.2018
Accepted : 15.12.2019

Keywords: Critical level, murate of potash, grain yield, balanced nutrition, crop response.

Introduction

Teff, *Eragrostis tef* (Zucc.) Trotter is a warm season annual grass native to Ethiopia (Ketema, 1997). It is adapted to environments ranging from drought-stressed to waterlogged soil conditions (Menna et al., 2015). It is a small-grained cereal grass species that has been grown as a food crop in east Africa for thousands of years (D'Andrea, 2008) having the lowest yield per unit area compared with other cereals such as wheat. Some of the factors that cause low productivity are lodging, method of planting and fertilizer application and the combined effect of these factors resulting up to 22% reduction in grain and straw yield (Gebretsadik et al., 2009). Being labeled as one of the latest super foods of the 21st century, teff's international popularity is rapidly growing (Provost and Jobson, 2014; Renton, 2014; Secorun, 2016). Teff grain is gluten free, and is a good flour source for segments of the population suffering from gluten intolerance or Celiac's Disease

---

[*] Corresponding author.
Agricultural Transformation Agency (ATA), Addis Ababa, Ethiopia
Tel.: +251911367005
E-mail address: Mulugetadem@gmail.com

e-ISSN: 2147-4249
DOI: 10.18393/ejss.663486

(Miller, 2010). Teff is also an excellent source of fiber and iron, and has many times higher amounts of Ca, K and other essential minerals than in an equal amount of other grains (Piccinin, 2002). Nationally, teff is one of the important cereals that are at the center of the increasingly vibrant agricultural output markets of Ethiopia (Minten et al., 2014). It has the largest share of area (24%, 3.02 million hectares) of the grain crops and second (after maize) in terms of grain production (17.29%, 5.02 million tons) in Ethiopia (CSA, 2017).

Potassium (K) is one of the major plant nutrients and abundant element in soils. It is an essential plant nutrient playing an important role in various physiological and biochemical activities and is required in high amounts. Its uptake frequently exceeds the uptake of nitrogen, to maintain adequate crop growth (Mengel and Kirkby, 2001). Potassium plays a remarkable role in transpiration, stomatal opening and closing and osmoregulation (Cakmak, 2005). The higher K^+ content than the other cations in the plant tissues effectively regulates many physiological and biochemical processes (Bajwa, 1994). While involved in many physiological processes, K's impact on water relations, photosynthesis, assimilate transport and enzyme activation can have direct consequences on crop productivity (Oosterhuis et al., 2014). The production of less photosynthetic assimilates and reduced assimilate transport out of the leaves to the developing fruit greatly contributes to the negative consequences that deficiencies of potassium have on yield and quality production (Pettigrew, 2008).

Vertisols are dark, montmorillonite-rich clay soils with characteristic shrinking and swelling properties (FAO, 2015). They have high montmorillonite clay and when dry show cracks of at least 1 cm wide and 50 cm deep (Eswaran and Cook, 1988). Vertisols are important agricultural soils though primarily poor drainage and difficult workability limit nutrient availability and productivity, and therefore they require proper fertility management practices. In Ethiopian agriculture, Vertisols have an important place since they have diverse chemical properties and are widely distributed (over 12 m ha) covering 11% of the total land mass and the fourth important soil order (Mamo et al., 2002). An estimated 7.6 million ha of Ethiopian Vertisols are located in the central highlands, above 1500 m.a.s.l., and on higher elevations (> 2500 m.a.s.l.) in temperate ecosystems (Debele, 1985; El-Wakeel and Astatke, 1996). Evidence suggests there would be substantial increases in crop yields on Vertisols, if excess surface soil water is drained off and if appropriate cropping practices are used (Wubie, 2015).

Numerous studies reported the yield response of teff to N and P fertilization (Mirutse et al., 2009; Ayalew et al., 2011; Kidanemariam, 2013; Giday et al., 2014; Abebe and Workayehu, 2015). But, there was no detail study on the response of teff to K fertilization in Ethiopia. Unfortunately, application of K did not receive due attention in Ethiopian soils where it is believed to be 'adequate' in native K supply. It is widely recognized that information about crop response to fertilization, as well as nutrient use efficiency, soil nutrient balance and soil test requires updating and re-evaluation (Peck and Soltanpour, 1990). Currently, there is little national and/or regional emphasis on the effect of K fertilization, soil K balance or K critical level in cereals growing areas of the country. This is evident from the highly imbalanced fertilizer consumption ratio with respect to K in Ethiopia, where K fertilizer has not been imported for crop production until 2014. On the other hand, removal of K in proportion to N is very high in cropping systems, particularly in those involving cereal crops (Rana and Rana, 2011). In Ethiopia, application of nutrients other than N and P was started in 2014/15 cropping seasons through series fertilizer demonstrations conducted jointly by Ministry of Agriculture (MoA), Agricultural Transformation Agency (ATA) and partners using compound fertilizers containing other nutrients instead of Di ammonium phosphate (DAP). Application of potassium fertilizer was demonstrated in 2004 and resulted in increases of tons of wheat yields due to application of 50 kg ha^{-1} K_2SO_4 (Astatke et al., 2004). Similarly, other research works conducted in different locations and crops showed that application of potassium resulted in a significant yield increase of wheat (Haile and Mamo 2013; Hailu et al., 2015; Brhane et al., 2017), potato (Haile and Boke 2011; Ayalew and Beyene 2011; Shunka et al., 2016), teff and wheat (Mulugeta et al., 2017). Additionally, it is also common to see farmers in central highlands of Ethiopia applying wood ash on their Vertisols fields because of observing better growing condition due to the ash, which could be taken as an indication for the need of K application.

Both yield and quality, and thus the economic value of teff, could be strongly influenced by potassium fertilizer management. However, information pertaining to the level of K required for optimum yield of teff for different soil test K conditions in Ethiopia is lacking. In this paper, we present the results of field trials on the effect of different levels of K fertilizer on teff in Vertisols of the central highlands of Ethiopia. The objectives of the study were to diagnose teff yield response to K fertilizer at field level and to examine the relationship between soil available potassium and its concentration in the test crop.

Material and Methods

Description of the experimental sites

Field experiments were conducted in soils differing in soil nutrient status during 2015/16 and 2016/17 cropping seasons in the central highland Vertisols of Ethiopia. The locations are in similar agroecology and among the teff growing districts of the country (Figure 1). The experiment was conducted in 18 randomly selected sites: 12 in the first year and repeated in 6 of the sites. The weather data of the sites (Figure 2) were obtained from the National Meteorological Agency of Ethiopia (NMA, 2016).

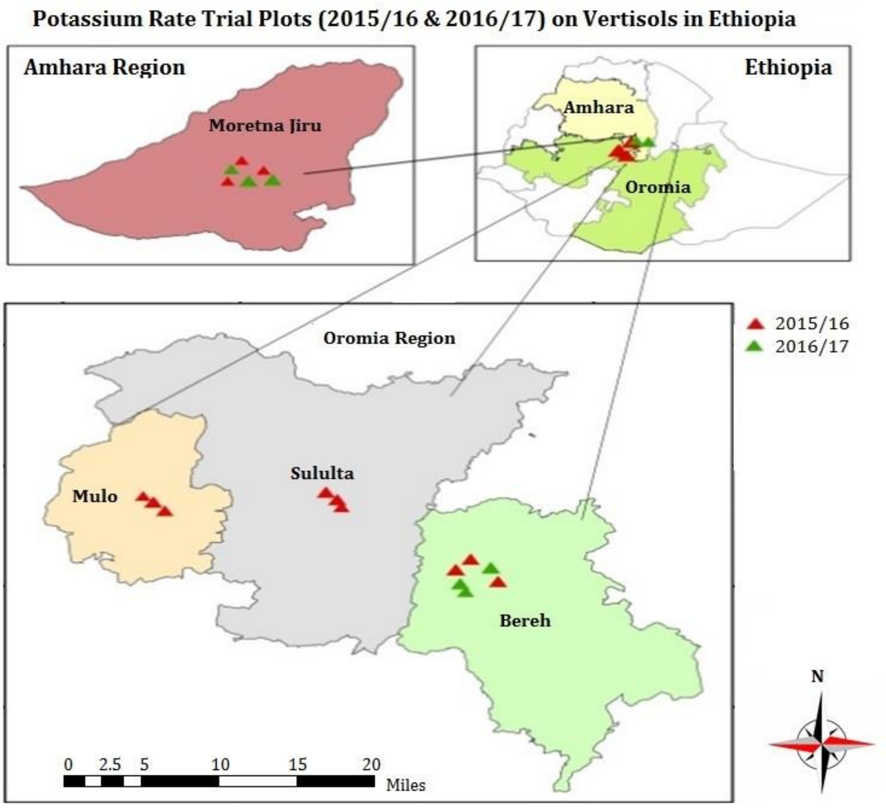


Figure 1. Geographic location of the experimental sites

Ten years (2007-2016) mean monthly minimum and maximum temperatures ranged from 17.9 to 23.9 ^{o}C while the mean monthly rainfall ranged from 4.1 to 387 mm with a bimodal pattern (Figure 2). The highest mean monthly rainfall and the lowest mean monthly temperatures were recorded between July and August (Figure 2).

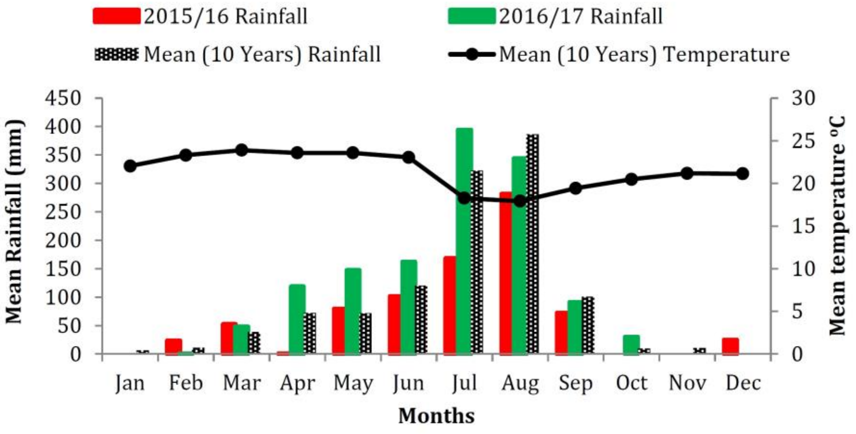


Figure 2. Mean monthly rainfall and temperature of the study sites for the last ten years (2007-2016) and rainfall during 2015/16 and 2016/17 cropping seasons

The mean rainfall of the two cropping seasons showed similar pattern with the mean long-term average of 96 mm per annum (Figure 2) but the amount in 2016/17 was higher than the long-term average. On the other hand, the mean monthly temperature of the two growing seasons was very much similar, both in amount and pattern, to the long-term average (Figure 2).

Experimental design and treatments

Each experiment had five levels of potassium *viz* 0, 30, 60, 90 and 120 kg K ha^{-1} in the form of KCl (murate of potash, 60% K_2O) as basal application. Based on previous national soils survey data that showed deficiency of nitrogen (N), phosphorus (P), sulfur (S), and zinc (Zn) in the experimental sites and considering 30 kg N/ton of grain and the ratio of the different nutrients, optimum rates of N, P, S and Zn at the rates of 120, 60, 15, and 3 kg ha^{-1} respectively were applied using N-P-S-Zn compound fertilizer (12-45-0 + 5 S + 1 Zn). The full amount of P, K, S, Zn, and 1/3 of N were applied during planting. The remaining 2/3 N was applied as top dressing at 30 days after sowing using urea. The treatments were arranged in a randomized complete block design (RCBD) with three replications at each trial site having a net plot size of 4 x 6 m. Improved teff variety, Quncho, seeds were sown between last week of July and first week of August by drilling along the rows spaced at 20 cm intervals at a seed rate of 10 kg ha^{-1}. The experimental fields were managed following the recommended management practices for teff in the areas.

Soil and plant sampling and analysis

Soil samples were obtained by collecting 15 random surface (0-20 cm) augur samples to make one composite for each experimental site prior to sowing the crop during both seasons. The soil samples were well mixed, air dried, ground, and passed through a 2 mm sieve and analyzed for selected physico-chemical properties.

The particle size distribution was determined by the HORIBA-Partica (LA-950V2) laser scattering particle size distribution analyzer (Agrawal et al.,1991) and LA-950 software version 7.01 for Windows (Horiba, 2010), soil pH (glass electrode, soil/water ratio of 1:2.5); CEC was predicted from mid infrared spectra of soil samples. Exchangeable K, Ca, and Mg and available P, Sulfate-S and extractable Zn were extracted following Mehlich-3 procedure (Mehlich, 1984).

At maturity, the above ground biomass was harvested and weighed from 2mx3m area. 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 at 65°C until constant weight. The dried plant samples were powdered in a warring stainless-steel grinder. Dry powdered plant samples were ashed in a muffle furnace at 500 ºC and extracted in 10 ml of 6M HCl and dried on hot plate for 15 minutes at 140 ^{o}C. The dried ash was dissolved in 10 ml of 1M HCl and the nutrient contents in the filtrate were analyzed using Inductive Couple Plasma (ICP).

Data collection and analysis

Ten plants were randomly selected from each plot at maturity for recording plant height, panicle length and number of fertile tillers per plant. At harvest, all plants from a 2 m x 3 m plot area were harvested, air dried, and manually threshed to determine straw, grain and total biomass yields per plot, which were later converted to yields per hectare. Grain yields were adjusted to approximately l2% moisture content. The data were analyzed using the general linear model (GLM) procedures of the SAS 9.2 statistical software (SAS Institute Inc, 2008) to evaluate the effect of K levels on yield and yield components of teff. Total nutrient uptakes of the different nutrients were computed by multiplying the concentrations of the nutrients and total yield. Separate analysis was also conducted for each sites and year. Least Significant Difference (LSD) test at $P \leq 0.05$ was used to separate means whenever there were significant differences.

Results and Discussion

Physical and chemical properties of the soils

The experimental soils were clayey in texture, whereby the proportions of sand, silt and clay varied from 3.75 to 27.78, 6.03 to 23.28 and 50.26 to 90.22% respectively, indicating that clay was the most dominant fraction in the soils (Table 1).

The values of soil pH (H_2O) ranged from 5.4 to 7.4 showing that most of the soils were slightly acidic to neutral in reaction. Based on the K critical levels generated for teff (Mulugeta et al., 2019), which categorized the Mehlich-3 K of <210, 210-280, 280-500, and >500 mg kg^{-1} as low, medium, high and very high respectively; the K values of the study soils were in the range from low to very high. On the other hand, according to EthioSIS (2013, 2016) which categorized Mehlich-3 K values of < 90, 90-190, 190-600, 600-900 and >900 mg kg^{-1} as very low, low, optimum, high and very high; the K status of the soils are in the range of low to medium.

Additionally, the available P, S and Zn contents of the experimental soils were also in the low to medium range, whereas available B was medium (Table 1) in accordance with EthioSIS (2013, 2016). The study also showed that the range of Ca and Mg was very high according to (Hazelton and Murphy, 2007) and the concentrations of basic cations were in the order of Ca > Mg > K. From a crop nutrition viewpoint, therefore, the levels of Ca and Mg were adequate to support optimum production of arable crops.

Table 1. Mean values of selected physico - chemical properties of surface soil (0-20 cm) of the experimental sites before planting.

Trial Site	Sand	Silt	Clay	pH	CEC	Av. P	Ex. K	Av. S	Ex. Ca	Ex. Mg
		%		1:2.5	(Cmol (+) kg^{-1})			(mg kg^{-1})		
2015/16										
1	4	6	90	6.1	62	18	170	12	5696	1006
2	10	13	77	5.6	36	6	255	12	7322	1132
3	9	16	75	5.7	55	10	305	13	6801	1324
4	16	18	65	5.4	49	5	282	17	5501	1224
5	19	20	60	5.6	49	20	526	13	5283	1157
6	28	22	50	5.5	45	4	360	19	5408	1178
7	13	19	68	6.3	55	13	343	11	6198	1061
8	14	20	66	6.9	62	15	356	21	7986	1000
9	13	23	64	6.4	54	4	281	18	6546	1004
10	6	8	85	6.2	64	11	225	13	7241	1320
11	9	9	82	6.6	57	3	248	13	9869	1069
12	10	14	76	7.4	73	33	197	15	5809	1171
2016/17										
13	6	11	83	6.3	70	9	264	19	6931	1464
14	9	15	76	5.8	64	9	261	20	8042	1308
15	12	15	73	5.5	62	6	272	19	7649	1462
16	8	19	74	5.6	63	3	331	19	5725	1044
17	8	23	69	6.4	59	7	316	28	5406	1028
18	9	23	68	6.7	58	11	291	29	6239	1274

Av.: available; Ex.: exchangeable;

A soil is regarded "ideal" if the percent base saturations of Ca, Mg and K are in the ranges 65-85, 6-12 and 2-5, respectively (AgKnowledge, 2011). In the present study, the results of the basic cations showed that the percent base saturations of Ca, Mg and K ranged from 70-84, 15-26 and 1-4, respectively indicating that the concentrations of Ca was within the ideal range, whereas that of Mg and K are higher and lower, respectively, than the suggested ideal range. The CEC ranged from 36- 73 Cmol (+) kg^{-1} which was high and very high according to the rating of Hazelton and Murphy (2007). The very high value of CEC is mainly due to high clay content and predominance of 2:1 layer clay minerals. It was in line with Debele (1985) who reported that nearly all the Vertisols have high CEC of 35–70 cmol(+) kg^{-1}.

Effect of K application on teff grain and straw yields

The results showed that grain and straw yields were significantly affected by application of K in 67% of the tested locations, although the responses varied by sites and year (Table 2). Applications of 60 and 90 kg K ha^{-1} were found to be optimum in 23 and 44% of the locations, while the lowest yields were recorded at 0 kg K ha^{-1} across the sites. The result also showed that when the initial K concentration is less than 300 mg kg^{-1}, application of 90/60 kg K ha^{-1} is required. Besides, higher yields in all treatments were observed in the 2016/17 cropping season than the 2015/16 season, although the yield increments due to increasing levels of K were higher in 2015/16 as compared to that of 2016/17 (Table 2). Despite the increment of yields due to K application, the response was not economically feasible in 33% of the test locations and hence the results and discussion in this paper include only the data obtained from 67% of the tested locations.

Grain and straw yields were significantly increased due to application of K (Table 2). The grain yield, which is a function of combined contribution of various yield components, has direct relationship with the growing conditions and management practices of the crop. The increase in grain and straw yields due to the application of K might be due to enhanced accumulation of assimilates, which resulted in heavier grains and straws, and also the involvement of K in physiological and biochemical processes (Wang et al., 2013) resulting in more dry matter production through improvements in plant height and number of tillers per plant.

The lowest grain and straw yields in the control might be attributed to an imbalance uptake of essential elements such as N, P and K, which resulted in poor performance of yield attributes. Low K results in an overall reduction of the amount of photosynthetic assimilates available for growth (Pettigrew, 2008). Our result is in line with the findings of Alam et al. (2010), which showed a significant increase in grain, straw and total biomass yields of wheat when higher dose of K was applied. Positive responses of different crops to K application in terms of growth, yield and potassium accumulation were also reported by different researchers, e.g. sunflower (Chhajro et al., 2014), maize (Nawaz et al., 2006), tomato (Akhtar et al., 2010) and cotton (Zia-Ul-Hassan and Arshad, 2010; Zia-ul-Hassan et al., 2014) .

Table 2. Mean teff grain and straw yields as influenced by increasing K levels at the experimental sites in: 2015/16 and 2016/17

		2015/16									2016/17								
Yield & yield components	Trial sites	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11	Site 12	Site 13	Site 14	Site 15	Site 16	Site 17	Site 18
	Initial STK (mg kg^{-1})	170	256	305	282	526	360	344	356	281	225	248	197	291	316	331	261	264	272
Grain Yield (kg ha^{-1})	Treatments (kg K ha^{-1})	***	***	***	***	NS	***	***	***	*	***	***	***	***	***	**	***	***	***
	0	1362^{d}	1563^{c}	1642^{c}	1665^{c}	2139	1960^{d}	2088^{c}	2106^{c}	1822^{c}	1747^{c}	1766^{c}	1846^{d}	2140.7^{d}	2315.3^{d}	2989.4^{b}	2164.0^{d}	2143.3^{d}	2461.0^{d}
	30	1555^{c}	1704^{c}	1766^{bc}	1965^{b}	2213	2050^{c}	2538^{b}	2929^{ab}	1939^{bc}	2443^{b}	2537^{b}	2453^{c}	2210.0^{c}	3332.4^{b}	3247.2^{a}	2253.0^{c}	2212.7^{c}	3114.7^{bc}
	60	1838^{b}	1879^{b}	2175^{a}	2161^{a}	2169	2140^{b}	3150^{a}	3091^{ab}	1983^{b}	2886^{a}	2732^{ab}	2761^{b}	2314.7^{b}	3498.5^{a}	3445.7^{a}	2355.7^{b}	2325.7^{b}	3222.9^{b}
	90	2405^{a}	2475^{a}	1890^{b}	2144^{a}	2162	2243^{a}	3050^{a}	3191^{a}	2136^{a}	2881^{a}	2990^{a}	3127^{a}	2456.3^{a}	3053.8^{c}	3322.7^{a}	2432.3^{a}	2437.0^{a}	3391.7^{a}
	120	1884^{b}	1888^{b}	1845^{b}	1876^{b}	2147	2008^{dc}	3000^{a}	2844^{b}	1852^{c}	2800^{a}	2630^{b}	2537^{bc}	2280.0^{b}	3011.9^{c}	2974.4^{b}	2338.7^{b}	2436.3^{a}	3057.3^{c}
	CV	2.63	4.35	4.45	2.53	2.55	1.89	3.28	5.14	3.28	3.97	5.53	5.59	1.28	2.49	3.34	1.28	1.00	2.36
Straw Yield (kg ha^{-1})	Treatments (kg K ha^{-1})	***	***	**	**	*	**	***	***	***	***	*	**	***	***	*	***	***	***
	0	3731^{b}	4420^{c}	5038^{c}	5111^{c}	7707^{b}	6598^{b}	5748^{c}	6129^{c}	5563^{b}	5069^{c}	5624^{c}	5796^{c}	6010.0^{c}	6342.8^{d}	7988.4^{bc}	5734.0^{d}	5963.7^{b}	6794.6^{d}
	30	4087^{b}	4609^{c}	5381^{bc}	5623^{bc}	8321^{a}	5826^{c}	6677^{b}	7538^{b}	5603^{b}	6069^{b}	6464^{bc}	6680^{b}	6385.7^{b}	8799.0^{a}	8385.1^{ab}	6810.0^{a}	6738.8^{a}	8238,6^{b}
	60	3916^{b}	4488^{c}	6251^{a}	6425^{a}	7923^{b}	6718^{ab}	7975^{a}	7889^{ab}	5625^{b}	6985^{b}	7827^{a}	6335^{bc}	6862.7^{a}	8664.3^{a}	8410.6^{ab}	6592.2^{b}	6760.6^{a}	7797.8^{c}
	90	5616^{a}	6408^{a}	5419^{bc}	6400a	7953^{b}	7132^{a}	7843^{a}	8180^{a}	5705^{b}	6972^{b}	7522^{ab}	8113^{a}	6792.0^{a}	7071.2^{c}	8495.5^{a}	6724.0^{a}	6710.4^{a}	8687.6^{a}
	120	5676^{a}	5293^{b}	6009^{ab}	5914^{ab}	7855^{b}	6511^{b}	7692^{a}	7501^{b}	6434^{a}	8055^{a}	6742^{abc}	6568^{bc}	6413.3^{b}	7863.5^{b}	7729.0^{c}	6457.0^{c}	6828.6^{a}	8186.7^{b}
	CV	6.18	6.36	6.38	5.00	2.13	4.13	4.04	4.49	2.16	7.44	9.55	6.58	1.56	2.64	2.97	0.76	1.08	1.44

Significant at * $P \leq 0.05$;** $P \leq 0.01$; *** $P \leq 0.001$ and below; **CV**: Coefficient of variations; Means followed by same letter(s) within a column do not differ at $P \leq 0.05$

Increasing K levels beyond 60 kg ha^{-1} in some locations and 90 kg ha^{-1} in others, however, decreased all the yield and yield components, most probably due to nutrient imbalances caused by excess potassium on other nutrients such as N, and antagonistic effect of K^+ on Ca^{2+} and/or Mg^{2+} (Saifullah et al.,, 2002). The results might also be due to higher affinity of K^+ for membrane carriers compared to other cations. Thus, with the increase of K^+ concentrations in the soil, competition increases at the binding sites of membrane carriers, which might have decreased the uptake of Ca^{2+} (Marschner, 2011). In the nutrient uptake processes; K, Mg, and Ca are strongly antagonistic (Voogt, 2002) resulting in a deficiency of the depressed nutrient. Soils with a low CEC are more likely to develop deficiencies in potassium (K^+), magnesium (Mg^{2+}) and other cations while high CEC soils are less susceptible to leaching of these cations (Cornell University Cooperative Extension, 2007).

The yield increments due to application of K varied significantly ($P<0.0001$) between the treatments and the cropping seasons (Table 2). Higher values of yield and yield components were recorded in the 2016/17 than 2015/16 season, although the relative yield increments over the control were higher in 2015/16 as compared to that of 2016/17. The high variability of yield and yield components between the two cropping seasons could be due to the variation in rainfall, where the amount and distribution of rainfall was better in the 2016/17 (Figure 2), which in turn might have affected the nutrient availability and the response to applied K. Similar results were reported by Sangakkara et al. (2001) and Catuchi et al. (2012) who showed that K applied as nutrient solution promoted greater growth and development of the plants under drought than unstressed conditions.

The relatively higher yield increments over the control in 2015/16 might be attributed to the influence of K on plant growth during water stress (Marschner, 2012). Catuchi et al. (2012) and Guareschi et al. (2011) indicated that appropriate levels of K in the plant tissues enable better plant development and growth, and increased K availability in the soil enhances plants to exploit a larger soil volume due to better development of their root system, which also improves the support during drought (Sangakkara et al., 2001; Wang et al., 2013; Zörb et al., 2014).

The high variability in response to applied K between experimental sites could probably be related to site differences in initial soil physical and chemical properties such as clay content, moisture content, Ca and Mg contents and the soils' K status (Table 1). Minerals K release to soluble and exchangeable forms and K adsorption by exchange sites depend on the equilibrium between different phases of soil K, which may be affected by such factors as root uptake, applied fertilizer K, soil moisture, soil pH and soil temperature (Niu et al., 2011; Britzke et al., 2012).

Potassium sorption on exchange sites and its fixation depend on the physicochemical properties of the soil, as well as type and content of the clay minerals (Braunschweigh, 1980). More clay contents possessed more K^+ contents whether fixed or exchangeable (Jalali and Zarabi, 2006). The fate of K^+ fertilizers applied to the soil depends upon the clay contents, clay minerals and fractions of K^+ already available in the soil (Wakeel et al., 2013). The amount of water in the soil affects the aeration of the soil, which eventually decreases the K availability possibly due to the negative effects on K-mobility (Afari-Sefa et al., 2004). Soil moisture also affects K availability by affecting both K mobility and root growth (Kuchenbuch et al., 1986).

Effect of K application on nutrient concentrations in teff tissue

In majority of the experimental sites, increasing K rate up to 60/90 kg K ha^{-1} increased nutrient concentrations in the biomass. The influences of site and season on plants nutrient concentrations were also apparent. However, the concentrations of P, Ca and Mg were not significantly influenced by increasing levels of K (Table 3).

Table 3. ANOVA for nutrient concentration across location and year

Source	Nutrient concentration in teff biomass				
	N	P	K	Ca	Mg
	Pr > F				
Year (Yr)	<.0001	0.6994	<.0001	<.0001	0.0278
Location (Loc)	0.0016	<.0001	0.0193	<.0001	0.0002
Yr*Lc	0.2473	<.0001	0.0200	0.0609	0.0050
Block (Yr*Loc)	0.4351	0.7711	0.0466	0.0006	0.0191
Treatment (TT)	0.0016	0.0596	0.0001	0.0122	0.1694
Yr*TT	0.8065	0.8709	0.4076	0.5260	0.4490
Loc*TT	0.0309	0.7666	0.3837	0.3666	0.6873
Yr*Loc*TT	0.9750	0.9998	0.1206	0.6057	0.3659
CV	9.56	19.72	12.83	17.50	42.09

Potash application increased the nitrogen content in teff biomass (Table 4) though significant ($P < 0.01$) increments in nitrogen concentration due to K level were observed only at 3 locations. This could be attributed to imbalance between N and K as also reported by Wahhab and Hussain (1957). Crop response to applied nitrogen fertilizers decreases when the exchangeable potassium content of a soil is below the optimal level and vice versa (Rutkowska et al., 2014; Pradhan et al., 2015). Positive interaction between N and K at balanced supply might be the reason for the increased N concentration in plants. Besides, K also influences nitrogen absorption and reduction, and rapid nitrogen (NO_3) uptake depends on adequate K in the soil solution (IPNI, 1998). This result is consistent with the findings of Ashok et al. (2009).

The differences in N concentrations in the plant tissues at the different sites might be attributed to differences in the physicochemical properties of the experimental soils (Table 1), whereas the differences in N concentration between the two seasons might have been caused by the variations in quantity and distribution of rainfall (Figure 2). Changes in precipitation would alter nitrogen (N) availability and mineralization directly via its impact on soil water availability, erosion and leaching, and indirectly by influencing plant N uptake as well as plant productivity. Increases in precipitation, specifically in large rain events, might lead to large leaching and run-off (Nearing et al., 2005), which could increase N loss and decrease N retention. Crop response to N applications in Vertisols is closely linked to soil moisture variations and, hence, to rainfall pattern (ICRISAT, 1989). Poor drainage, a common characteristic of Vertisols, creates periodic waterlogging (anaerobic) conditions, which favors fertilizer N loss through denitrification (Knowles, 1982). The relative importance of these processes depends on environmental variables such as soil pH, topsoil texture, soil profile characteristics, soil aeration, water supply and temperature, as well as human activities such as type, amount, placement and timing of N fertilizers, available carbon, crop residue management, tillage, soil compaction, drainage, irrigation, land use change and stocking rate on grassland.

Phosphorus concentration in plant biomass was less than 0.2%, which was less than what most crops need for normal growth (0.2 to 0.5%) P in tissue dry matter (Kalra, 1998; Hue et al., 2000;). It was also not significantly influenced by increasing rates of K application but the effect of year and location was significant (Table 3), though slight increments with increasing K levels up to 60/90 kg K ha^{-1} were observed. The increase in P concentration with increasing K levels might be due to the role of K in translocation of nutrients that lead to increased nutrients concentration in plants (Kumar et al., 2015). The relatively low phosphorus concentration in teff biomass might be due to the low level of P in the experimental soils (Table 1) and indicate inadequate supplement of P as fertilizer in the treatments. These results are in line with the findings reported by Roy (1990).

Increasing K application from 0 to 120 kg K ha^{-1} significantly increased its concentration in teff biomass during both growing seasons (Table 4). The highest values of K concentration in teff during both growing seasons were recorded at the application of 120 kg K ha^{-1} in five of the seven sites, whereas the lowest K concentration was obtained from the control treatment, which might be due to the low soluble K in soil solution of the experimental soils (Table 1). Thus, the increase in K concentration in teff with increasing K rates could be due to higher K uptakes by the plants. Kemmler (1983) stated that wheat and other cereal crops require as much K as N and in some cases the need for K exceeds N. Teff, being one of the cereals, is expected to have similar requirements for N and K as wheat. Similar to N, potassium concentration by plants also showed a similar increasing trend with dry matter production. In line with the present study, Kumar et al. (2015) noticed increase in concentration of different nutrients by wheat crop due to increased levels of potassium. The results were also in line with Baque et al. (2006) who reported that concentrations of N, P and K were enhanced by increasing levels of K.

Studies on N:P ratios of teff are lacking but a review by Sadras (2006) indicated that N: P ratios of cereals varied between 1 and 20. A major cause of the variability lies in variations between the supply of nutrients to crops and, in particular, the tendency of crops to absorb far more P than is needed to meet the immediate needs and to store it (Bollons and Barraclough, 1999). However, this cannot explain the variability in the N: P ratio when there is an optimal supply of nutrients (Greenwood et al., 2008). In this study, the N: P: K ratio was 1: 0.2: 0.9, indicating that N and K uptakes by teff are almost the same. MacLeod (1969) also reported that the percentages of N, P, and K in tissue below which final yield of grain decreased by 4.0, 0.7, and 4.0, respectively, for the plants sampled at heading.

The results showed that the ‘critical’ tissue K concentration, at which about 90% of the maximum yield was obtained, was 0.63% (Figure 3). This can also be taken as the internal K requirement for teff. This value was obtained at a site whose soil test value was 331 mg kg^{-1} with the application of 60 kg K ha^{-1}.

Table 4. Mean N, P K, Ca, and Mg concentrations (% dry matter) in teff above ground biomass as influenced by increasing rates of K at seven selected sites.

Selected Nutrients	Trial sites	Site 6	Site 8	Site 11	Site 13	Site 15	Site 17	Site 18
	Initial STK (mg kg^{-1})	360	356	247	291	331	264	272
N	Treatments (kg K ha^{-1})	**	*	*	NS	NS	*	NS
	0	0.91^{c}	0.80^{b}	0.93^{ab}	0.65	0.62	0.65^{bc}	0.68
	30	0.92^{c}	0.83^{ab}	1.03^{a}	0.71	0.70	0.75^{ab}	0.69
	60	0.99^{ab}	0.88^{a}	1.01^{a}	0.75	0.66	0.79^{a}	0.79
	90	1.04^{a}	0.89^{a}	0.98^{ab}	0.77	0.68	0.68^{bc}	0.69
	120	0.95^{bc}	0.89^{a}	0.82^{b}	0.75	0.69	0.61^{c}	0.64
	CV	3.39	3.43	9.95	14.96	10.84	8.22	13.74
P	Treatments (kg K ha^{-1})	NS	NS	NS	NS	NS	NS	NS
	0	0.11	0.13	0.14	0.12	0.08	0.18	0.12
	30	0.13	0.14	0.15	0.13	0.08	0.19	0.13
	60	0.13	0.14	0.12	0.14	0.09	0.19	0.16
	90	0.12	0.16	0.16	0.13	0.11	0.20	0.17
	120	0.12	0.15	0.15	0.12	0.09	0.18	0.14
	CV	17.30	16.98	20.81	21.18	19.33	13.22	26.90
K	Treatments (kg K ha^{-1})	NS	*	**	NS	NS	*	NS
	0	0.53	0.49^{b}	0.46^{b}	0.91	0.88	0.63^{b}	0.78
	30	0.54	0.46^{b}	0.50^{ab}	0.84	0.90	0.74^{ab}	0.82
	60	0.60	0.49^{b}	0.64^{a}	0.90	0.91	0.77^{ab}	0.79
	90	0.60	0.58^{ab}	0.54^{ab}	0.88	0.92	0.99^{a}	0.90
	120	0.61	0.71^{a}	0.62^{a}	0.94	0.95	0.77^{ab}	0.93
	CV	9.80	16.63	14.14	9.09	11.51	17.54	10.19
Ca	Treatments (kg K ha^{-1})	NS	NS	NS	NS	NS	*	NS
	0	0.17	0.18	0.18	0.21	0.20	0.25^{ab}	0.30
	30	0.15	0.14	0.18	0.21	0.23	0.24^{b}	0.28
	60	0.18	0.17	0.18	0.24	0.22	0.29^{ab}	0.25
	90	0.21	0.18	0.22	0.20	0.20	0.32^{a}	0.31
	120	0.20	0.21	0.20	0.25	0.23	0.26^{ab}	0.32
	CV	19.4	27.59	17.89	13.97	15.38	15.65	14.76
Mg	Treatments (kg K ha^{-1})	*	NS	*	NS	NS	NS	NS
	0	0.09^{b}	0.09	0.11^{ab}	0.09	0.08	0.13	0.14
	30	0.09^{b}	0.09	0.11^{ab}	0.10	0.09	0.14	0.14
	60	0.11^{ab}	0.09	0.10^{a}	0.11	0.09	0.17	0.14
	90	0.13^{a}	0.10	0.13^{a}	0.10	0.10	0.18	0.18
	120	0.11^{ab}	0.11	0.11^{ab}	0.11	0.10	0.31	0.15
	CV	18.24	18.62	11.48	12.05	16.83	67.72	18.39

Significant at * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$ and below; LSD- least significant difference; CV- Coefficient of variations; Means followed by same letter(s) within a column do not differ at $P \leq 0.05$.

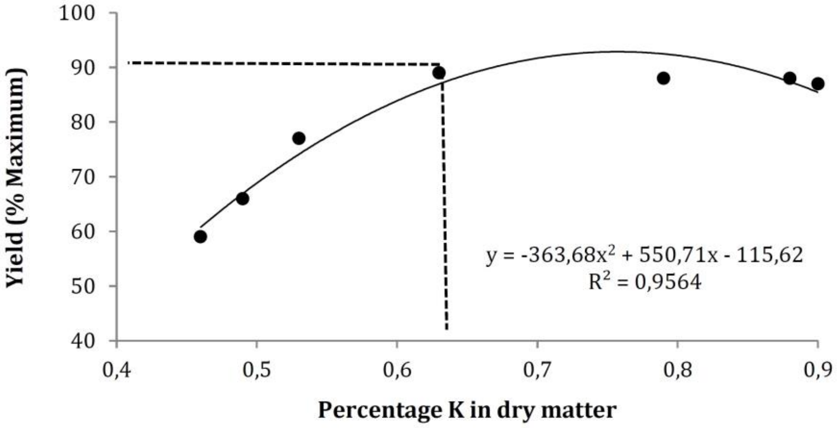


Figure 3. Relationship between K concentration in dry matter and relative yield

There was no statistically significant difference in Ca and Mg concentrations in teff biomass with increasing potassium rates (Table 3). It may be explained by the presence of very high Ca and Mg compared to K in the soil, which was not affected even by the application of K. The uptakes of K, Ca and Mg do not depend only on their concentrations in the soil, but also on their ratios. An excess application of one nutrient may induce deficiency of the others. K, Ca and Mg strongly interfere with each other during the uptake process (Voogt, 2002). High Ca and Mg concentrations in soil inhibit the uptake of K, while high K concentration in nutrient solution also inhibits the uptake of Ca and Mg (Bar-Tal and Pressman, 1996; Nukaya et al., 1997). But this did not happen in the present experiment might probably be as the amount of K was not so high compared to that of Ca and Mg to inhibit their uptakes.

Expressed as simple ratios, the "ideal" soil would have ratios of Ca: Mg about 7:1, Mg: K of 3.3:1 and Ca: K of 23:1 (AgKnowledge, 2011). The results from this study showed that the ratios of Ca: K ranged from 20:1 to 78:1 while that of Ca: Mg was from 3:1 to 6:1 indicating the absence of cation imbalances. On the other hand, the K:Mg ratios were between 0.05:1 and 0.14:1, the average being 0.08:1, showing much lower value than the critical level (0.7:1) suggested by Loide (2004). According to the suggestion by the author, all plots should have been affected by Mg induced K deficiency and responses to application of K fertilizer should have been observed. However, economically significant responses (data not shown) were not observed on soil K tests above 264 mg kg^{-1} (Figure 4). The average proportions of Ca, Mg and K in the experimental soils were 75, 23 and 2% respectively showing normal base saturation ranges of an "ideal" soil. Ologunde and Sorensen (1982) indicated that, when a soil contains adequate absolute quantities of Ca, Mg and K, the ratios of these cations (Ca/ Mg, Ca/K, and K/Mg) do not generally influence plant yield within the ranges commonly found in soils showing that total availability or supply is typically more important than the ratios.

Additionally, the relationships between relative yield (RY) and K concentration as well as RY and the cation ratios (Ca: K, and Mg: K (Figure 4) showed that application of K is required only for soils whose soil test K are below 264 mg kg^{-1}, Ca: K > 50:1 and Mg: K ratio > 15:1 (Figure 5) and responses to the application of K fertilizer was also observed on these soils at the rates of 60/90 kg K ha^{-1}.

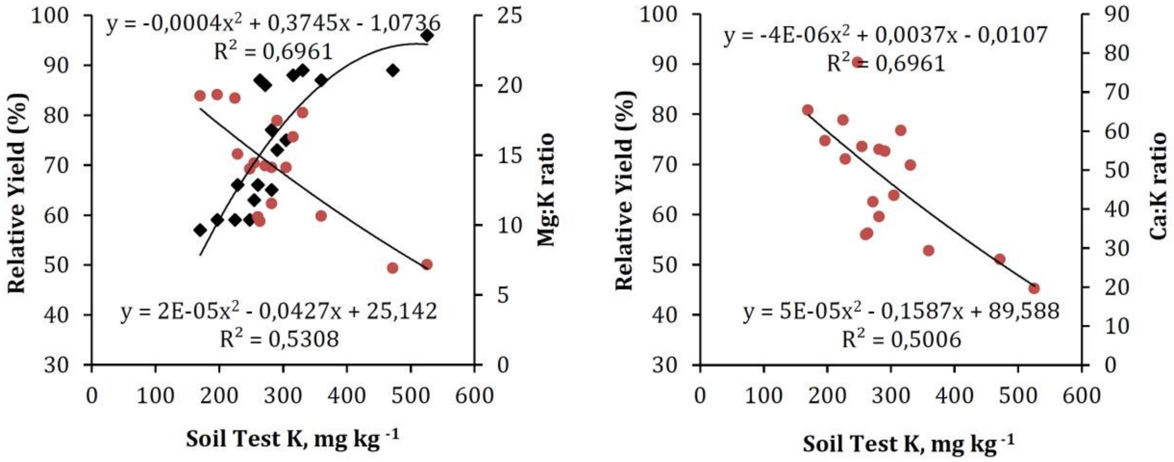


Figure 4. Relationship between soil test K and relative yield; soil test K and cation ratios

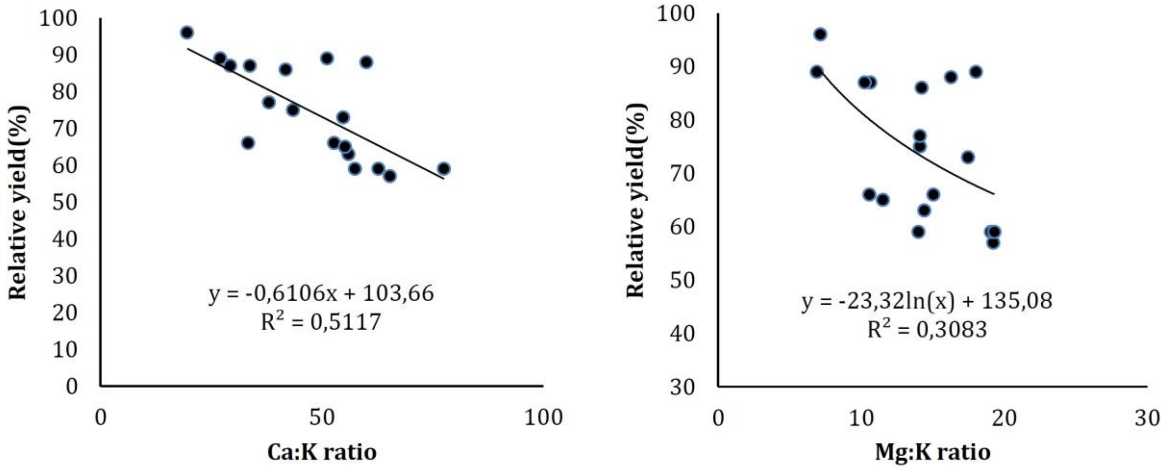


Figure 5. Relationship between cation ratios and relative yield

Conclusion

Potassium is one of the principal plant nutrients determining crop yield and quality. However, K application is not part of the fertilizer program in Ethiopia. Application of K in the study sites could increase yield of teff, reduce the negative potassium balance caused by the absence of K fertilizer and high amounts of K removed through grain and straw harvests.

Our two years on-farm research trials clearly demonstrated significant increase of teff yield with K fertilization for the study sites. Application of K increased grain yield of teff up to 77% over the control (no K). About 44% of the sites showed significant responses to application of 60 kg K ha^{-1} while 90 kg K ha^{-1} resulted in significant yield increases in 23% of the sites. The responsive sites had initial soil test K values ranging from 166 to 282 mg kg^{-1}, which were different from the critical levels developed by EthioSIS program for Ethiopian soils. The concentrations of major nutrients like N and K were also affected by K fertilization in most locations. Different responses of teff to increasing levels of K were obtained from different sites showing the need for developing critical K levels for the different soils. In addition, our result advocates the importance of balanced K nutrition in the study sites and similar areas, particularly where soil potassium level is low and in responsive Vertisols for better crop yields.

Acknowledgements

This study was funded by international Potash Institute (IPI) Israeli Chemicals Limited (ICL) and Agricultural Transformation Agency (ATA). We deeply appreciate and acknowledge the volunteer teff growing farmers without whom the work could not have been done, woreda experts and development agents in the districts where the trials were conducted, for their assistance in implementing the field work.

References

Abebe, B., Workayehu, T., 2015. Effect of method of sowing and time of di-ammonium phosphate (DAP) fertilizer application, on yield and yield components of Tef ((Eragrostic tef) Trotter) at Shebedino, Southern Ethiopia. *Advances in Crop Science and Technology* 3: 168.

Afari-Sefa, V., Kwakye, P.K., Okae-Anti, D., Imoro, I.A., Nyamiah, M., 2004. Potassium Availability in Soils – Forms and Spatial Distribution, The Abdus Salam International Centre for Theoretical Physics (ICTP), Preprint No.110, IC 2004, Trieste, Italy.

AgKnowledge, 2011. The fertiliser review. Issue 2. 6p. Available at [Access date: 19.02.2018]: http://agknowledge.co.nz/publications

Akhtar, M.E., Khan, M.Z., Rashid, M.T., Ahsan, Z., Ahmad, S., 2010. Effect of potash application on yield and quality of tomato (*Lycopersicon Esculentum* Mill.). *Pakistan Journal of Botany* 42(3): 1695–1702.

Alam, M.R., Ali, M.A.. Molla, M., Momin, M., Mannan. M., 2010. Evaluation of different levels of potassium on the yield and protein content of wheat in the high Ganges river floodplain soil. *Bangladesh Journal of Agricultural Research* 34(1): 97-104.

Ashok, Singh, J.P., Kumar, N.C., Singh, G.R., 2009. Effect of the levels of potassium and manganese on the uptake of N, P, and K and yield of wheat. *Journal of Agricultural Physics* 9: 28–32.

Astatke, A., Tekalign, M., Peden, D., Diedhiou, M., 2004. Participatory on-farm conservation tillage trial in the Ethiopian highland Vertisols: The impact of potassium application on crop yields. *Experimental Agriculture* 40(3): 369–379.

Ayalew, A., Beyene, S., 2011. The influence of Potassium Fertilizer on the Production of Potato (*Solanum tuberosu* l.) at Kembata in Southern Ethiopia. *Journal of Biology, Agriculture and Healthcare* 1(1): 1–13.

Ayalew, A., Kena, K., Dejene, T., 2011. Application of NP Fertilizers for Better Production of Teff (*Eragrostis tef (zucc.)* trotter) on Different Types of Soils in Southern Ethiopia. *Journal of Natural Sciences Research* 1: 6–15.

Bajwa, M.I., 1994. Soil potassium status, potash fertilizer usage and recommendations in Pakistan. Potash Review No. 3., Basel, Switzerland: International Potash Institute. 4 p.

Baque, M.A., Karim, M.A. Hamid, A., Testsushi, H., 2006. Effects of fertilizer potassium on growth, yield and nutrient uptake of wheat (*Triticum aestivum*) under water stress conditions. *South Pacific Study* 27(1): 25–35.

Bar-Tal, A., Pressman, E., 1996. Root restriction and potassium and calcium solution concentrations affect dry-matter production, cation uptake, and blossom-end rot in greenhouse tomato. *Journal of the American Society for Horticultural Science* 121(4): 649–655.

Bollons, H.M., Barraclough, P.B., 1999. Assessing the phosphorus status of winter wheat crops: inorganic orthophosphate in whole shoots. *The Journal of Agricultural Science* 133(3): 285–295.

Braunschweigh, I.C., 1980. K^+ availability in Relation to Clay Content. Results of field experiment. *Potash Review* 2: 1–8.

Brhane, H., Mamo, T., Teka, K., 2017. Optimum potassium fertilization level for growth, yield and nutrient uptake of wheat (*Triticum aestivum*) in Vertisols of Northern Ethiopia. *Cogent Food & Agriculture* 3: 1347022.

Britzke, D.,.da Silva, L.S., Moterle, D.F., dos Santos Rheinheimer, D., Bortoluzzi, E.C., 2012. A study of potassium dynamics and mineralogy in soils from subtropical Brazilian lowlands. *Journal of Soils and Sediments* 12(2): 185–197.

Cakmak, I., 2005. The role of potassium in alleviating detrimental effects of abiotic stresses in plants. *Journal of Plant Nutrition and Soil Science* 168(4): 521–530.

Catuchi, T.A., Guidorizzi, F.V.C., Guidorizi, K.A., Barbosa, A.D.M., Souza. G.M., 2012. Physiological responses of soybean cultivars to potassium fertilization under different water regimes. *Pesquisa Agropecuária Brasileira* 47(4):519-527.

Chhajro, M.A.,Zia-ul-hassan, Shah, A.N., Talpur, K.H., Kubar, K.A., 2014. Response of two hybrid sunflower genotypes to applied different levels of soil potassium. *Persian Gulf Crop Protection* 3(2): 45-52.

Cornell University Cooperative Extension. 2007. Cation Exchange Capacity (CEC). Fact Sheet 22. Available at [Access date: 19.02.2018]: http://nmsp.cals.cornell.edu/publications/factsheets/factsheet22.pdf

CSA, 2017. Central Statistics Agency of Ethiopia. Report on area and production of major crops. Addis Ababa, Ethiopia.

D'Andrea, A.C., 2008. T'ef (Eragrostis tef) in ancient agricultural systems of highland Ethiopia. *Economic Botany* 62(4): 547–566.

Debele, B., 1985. The Vertisols of Ethiopia: their properties, classification and management. In: Fifth Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation, Wad Medani. World Soil Resources Reports, No. 56. FAO (Food and Agriculture Organization), Wad Medani, Sudan, pp. 31–54.

El-Wakeel, A., Astatke, A., 1996. Intensification of agriculture on vertisols to minimize land degradation in parts of the Ethiopian Highlands. *Land Degradation & Development* 7(1): 57–67.

Eswaran, H., Cook, T., 1988. Classification and management-related properties of Vertisols. In: Management of vertisols in Sub-Saharan Africa. Jutzi, S.C., Haque, I., Melntire, J., Stares, J.E.S. (Eds.). ILCA, Addis Ababa, Ethiopia. pp.64-84.

EthioSIS, 2013. Ethiopian Soils Information System (EthioSIS). Towards improved fertilizer recommendations in Ethiopia – Nutrient indices for categorization of fertilizer blends from EthioSIS woreda soil inventory data. Addis Ababa, Ethiopia.

EthioSIS, 2016. Ethiopian Soils Information System (EthioSIS). Soil fertility status and fertilizer recommendation atlas of Amhara National Regional State, Ethiopia. Addis Ababa, Ethiopia.

Gebretsadik, H., Haile, M., Yamoah, C.F., 2009. Tillage Frequency, Soil Compaction and N-Fertilizer Rate Effects on Yield of Teff (Eragrostis Tef (Zucc) Trotter) in Central Zone of Tigray, Northern Ethiopia. *Momona Ethiopian Journal of Science* 1(1): 82–94.

Giday, O., Gibrekidan, H., Berhe, T., 2014. Response of teff (Eragrostis tef) to different rates of slow release and conventional urea fertilizers in vertisols of southern Tigray, Ethiopia. *Advances in Plants & Agriculture Research* 1(5): 190-197.

Greenwood, D.J., Karpinets, T.V., Zhang, K., Bosh-Serra, A., Boldrini, A., Karawulova, L., 2008. A unifying concept for the dependence of whole-crop N : P ratio on biomass: Theory and experiment. *Annals of Botany* 102(6): 967–977.

Guareschi, R.F., Gazolla, P.R., Perin, A., Santini, J.M.K., 2011. Antecipated fertilization on soybean with triple superphosphate and potassium chloride coated with polymers. *Ciência e Agrotecnologia* 35(4): 643-648.

Haile, W., Boke, S., 2011. Response of Irish potato (Solanum tuberosum) to the application of potassium at acidic soils of Chencha, Southern Ethiopia. *International Journal of Agriculture and Biology* 13(4): 595-598

Haile, W., Mamo, T., 2013. The Effect of potassium on the yields of potato and wheat grown on the acidic soils of Chencha and Hagere Selam in Southern Ethiopia. International Potash Institute. e-ifc No.35. Available at [Access date: 19.02.2018]: https://www.ipipotash.org/uploads/udocs/e-ifc-35-rf1.pdf

Hailu, H., Mamo, T., Keskinen, R., Karltun, E., Gebrekidan, H., Bekele, T., 2015. Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia. *Agriculture & Food Security* 4: 19.

Hazelton,. P., Murphy, B., 2007. Interpreting Soil Test Results. What Do All The Numbers Mean?, 2nd Edition. CSIRO Publishing, Collingwood, Australia. 152p.

Hue, N.V., Ikawa, H., Huang, X., 2000. Predicting Soil Phosphorus Requirements. In: Plant Nutrient Management in Hawaii's Soils, Approaches for Tropical and Subtropical Agriculture. Silva, J.A. (Ed.). University of Hawaii, Honolulu. pp. 95–99.

ICRISAT (International Crops Research Institute for the Semi-Arid tropics). 1989. Management of Vertisols for Improved Agricultural Production. In: Proceeding of an IBSRAM Inaugural Workshop, 18-22 February 1985, ICRISAT Center, India. ICRISAT, Patancheru, India. 275p.

IPNI, 1998. IPNI (International Plant Nutrition Institute), Potassium availability and uptake. *Better Crops* 82(3): 14–15. Available at [Access date: 19.02.2018]: http://www.ipni.net/publication/bettercrops.nsf/0/68FBD2B2A6A305BF852579800082035B/$FILE/Better%20Crops%201998-3%20p14.pdf

FAO, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No.106. Food and Agriculture Organization, Rome, Italy. Available at [Access date: 19.02.2018]: http://www.fao.org/3/i3794en/I3794en.pdf

Jalali, M., Zarabi, M., 2006. Kinetics of nonexchangeable-potassium release and plant response in some calcareous soils. *Journal of Plant Nutrition and Soil Science* 169(2): 196–204.

Kalra, Y.P., 1998. Handbook of Reference Methods for Plant Analysis. CRC Press Washington DC, USA. 300p.

Kemmler, G., 1983. Fertilising for high yield wheat. IPI- Bulletin 1. International Potash Institute, Berne, Switzerland. Available at [Access date: 19.02.2018]: https://www.ipipotash.org/uploads/udocs/IPI-BULLETIN1_FERTILISING_FOR_HIGH_YIELD_WHEAT.pdf

Ketema, S., 1997. Tef. Eragrostis tef (Zucc.) Trotter. Promoting the conservation and use of underutilized and neglected crops. Vol. 12 Institute of plant genetics and crop plant research, Gatersleben/International Plant Genetic Resources Institute, Rome, Italy.

Kidanemariam, A., 2013. Wheat crop response to liming materials and N and P fertilizers in acidic soils of Tsegede Highlands, Northern Ethiopia. *Agriculture, Forestry and Fisheries* 2(3): 126-135.

Knowles, R., 1982. Denitrfication. *Microbiology Reviews* 46(1): 43–70.

Kuchenbuch. R,, Claassen, N., Jungk, A., 1986. Potassium availability in relation to soil moisture I. Effect of soil moisture on potassium diffusion, root growth and potassium uptake of onion plants. *Plant and Soil* 95(2): 221–231.

Kumar, S., Dhar, S., Kumar, A., Kumar, D., 2015. Yield and nutrient uptake of maize (Zea mays)–wheat (Triticum aestivum) cropping system as influenced by integrated potassium management. *Indian Journal of Agronomy* 60(4): 511–515.

Laura, S. 2016. Teff could be the next quinoa as Ethiopia boosts exports. The Guardian. Available at [Access date: 19.02.2018]: https://www.theguardian.com/sustainable-business/2016/oct/14/teff-quinoa-ethiopia-boosts-exports-food-africa

Loide, V.2004. About the effect of the contents and ratios of soil's available calcium, potassium and magnesium in liming of acid soils. *Agronomy Research* 2(1): 71–82.

MacLeod, L.B. 1969. Effects of N, P, and K and their interactions on the yield and kernel weight of barley in hydroponic culture. *Agronomy Journal* 61(1): 26-29.

Mamo, T., Richter, C., Heiligtag, B., 2002. Phosphorus availability studies on ten Ethiopian Vertisols. *Journal of Agriculture and Rural Development in the Tropics and Subtropics* 103(2): 177–183.

Marschner, H., 2011. Mineral Nutrition of Higher Plants, 2nd Edition. Academic Press, 889p.

Marschner, P., 2012. Marschner's Mineral Nutrition of Higher Plants. 3rd Edition. Academic Press, 672p.

Mengel, K., Kirkby, E.A., 2001. Principles of plant nutrition, 5th Edition. Kluwer Academic Publishers. Dordrecht, The Netherlands. 807p.

Menna, A., Semoka, J.M.R., Amuri, N., Mamo, T., 2015. Wheat response to applied nitrogen, sulfur, and phosphorous in three representative areas of the central highlands of Ethiopia –I. *International Journal of Plant & Soil Science* 8(5): 1–11.

Miller, D., 2010. Teff Grass Crop overview and forage production guide. Available at [Access date: 19.02.2018]: https://www.kingsagriseeds.com/wp-content/uploads/2014/12/Teff-Grass-Management-Guide.pdf

Minten, B., Stifel, D., Tamru, S., 2014. Structural transformation in Ethiopia: Evidence from cereal markets. *The Journal of Development Studies* 50(5): 611–629.

Mirutse, F., Haile, M., Kebede, F., Tsegay, A., Yamoah, C., 2009. Response of Teff [*Eragrostis (teff) Trotter*] to phosphorus and nitrogen on vertisol at North Ethiopia. *Journal of the Drylands* 2(1): 8-14.

Mulugeta, D., Tekalign, M., Sheleme, B., Selamyihun, K., 2019. Potassium critical level in soil for Teff (Eragrostis tef (Zucc.) Trotter) grown in the central highland soils of Ethiopia. *SN Applied Sciences* 1: 958.

Mulugeta, D., Tekalign, M., Sokolowski, E., Nachmansohn, J., 2017. Potash fertilization of teff and wheat in the highlands of Ethiopia. International Potash Institute. e-ifc No.48. Available at [Access date: 19.02.2018]: https://www.ipipotash.org/publications/eifc-407

Nawaz, I., Zia-Ul-Hassan, Ranjha, A.M., Arshad, M., 2006. Exploiting genotypic variation among fifteen maize genotypes of Pakistan for potassium uptake and use efficiency in solution culture. *Pakistan Journal of Botany* 38(5): 1689–1696.

Nearing, M.A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M.H., Nunes, J.P., Renschler, C.S., Souchère, V., van Oost, K., 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. *Catena* 61(2-3): 131–154.

Niu, J., Zhang, W. Chen, X., Li, C., Zhang, F., Jiang, L., Liu, Z., Xiao, K., Assaraf, M., Imas, P., 2011. Potassium fertilization on maize under different production practices in the North China plain. *Agronomy Journal* 103(83): 822–829.

Nukaya, A., Goto, K., Jang. H.G., 1997. Effect of NH_4-N levels and K/Ca ratios in the nutrient solution on incidence of blossom-end rot and gold specks on tomato fruits grown in rockwool. In: Plant Nutrition for Sustainable Food Production and Environment. Developments in Plant and Soil Sciences. Ando, T., Fujita, K., Mae, T., Matsumoto, H., Mori, S., Sekiya, J. (Eds.). Vol 78. Springer, Dordrecht. pp. 969-970.

Ologunde, O.O., Sorensen, R.C., 1982. Influence of concentrations of K and Mg in nutrient solutions on sorghum. *Agronomy Journal* 74(1): 41–46.

Oosterhuis, D.M., Loka, D.A., Kawakami, E.M., Pettigrew, W.T., 2014. The physiology of potassium in crop production. *Advances in Agronomy* 126: 203–233.

Peck, T.R., Soltanpour, P.N., 1990. The principles of soil testing, In: Soil Testing and Plant Analysis. 3rd Edition. Westerman, R.L. (Ed.). Number 3 in the Soil Science Society of America Book Series. Soil Science Society of America, Inc. Madison, Wisconsin, USA. pp. 1–9.

Pettigrew, W.T., 2008. Potassium influences on yield and quality production for maize, wheat, soybean and cotton. *Physiologia Plantarum* 133: 670–681.

Piccinin, D., 2002. More About Ethiopian Food : Teff. EthnoMed: Ethiopian Food. Available at [Access date: 19.02.2018]: https://ethnomed.org/clinical/nutrition/more-about-ethiopian-food-teff

Pradhan A.K., Beura K.S., Das R., Padhan D., Hazra G.C., Mandal B., De N., Mishra V.N., Polara K.B., Sharma S., 2015. Evaluation of extractability of different extractants for zinc and copper in soils under long-term fertilization. *Plant, Soil and Environment* 61(5): 227–233.

Provost, C., Jobson, E., 2014. Move over quinoa, Ethiopia's teff poised to be next big super grain. The Guardian. Available at [Access date: 19.02.2018]: http://www.theguardian.com/global-development/2014/jan/23/quinoa-ethiopia-teff-super-grain

Rana, S.S., Rana, M.C., 2011. Cropping System. Palampur 176062, India. Available at [Access date: 19.02.2018]: https://pdfs.semanticscholar.org/1a52/6685055e2c8502a88bc24fee5aa36aff4fc0.pdf

Renton, A., 2014. Get a taste for teff, the Ethiopian superfood. The Guardian. Available at [Access date: 19.02.2018]: http://www.theguardian.com/global-development/poverty-matters/2014/jan/23/get-taste-for-teff-ethiopia-superfood

Roy, H.K., Kumar, A., Sinha, K., 1990. Response of wheat to potassium in red loam (Alfisols) soils of Ranchi. *Journal of Potassium Research* 6(1): 23-28

Rutkowska, A., Pikuła, D., Stępień, W., 2014. Nitrogen use efficiency of maize and spring barley under potassium fertilization in long-term field experiment. *Plant, Soil and Environment* 60(12): 550–554.

Sadras, V.O., 2006. The N:P stoichiometry of cereal, grain legume and oilseed crops. *Field Crops Research* 95(1): 13–29.

Saifullah, Ranjha, A.M., Yaseenand, M., Akhtar, M.E., 2002. Response of wheat to potassium fertilization under field conditions. *Pakistan Journal of Agricultural Sciences* 39:269–272.

Sangakkara, U.R., Frehner, M., Nösberger, J., 2001. Influence of soil moisture and fertilizer potassium on the vegetative growth of Mungbean (*Vigna radiata* L. Wilczek) and Cowpea (*Vigna unguiculata* L. Walp). *Journal of Agronomy and Crop Science* 81(2): 73–81.

SAS Institute Inc. 2008. SAS/STAT 9.2 User's Guide, in: SAS/STAT 9.2 User's Guide.

Shunka, E., Chindi, A., W/giorgis, G., Seid, E., Tessma, L., 2016. Response of potato (Solanum tuberosum L.) varieties to nitrogen and potassium fertilizer rates in central highlands of Ethiopia. *Advances in Crop Science and Technology* 4:.50.

Voogt, W., 2002. Potassium management of vegetables under ıntensive growth conditions. In: Potassium for sustainable crop production. Pasricha, N.S., Bansal, S.K. (Eds.). International Potash Institute, Bern, Switzerland. pp. 347-362

Wahhab, A., Hussain, I., 1957. Effect of nitrogen on growth, quality, and yield of ırrigated wheat in west Pakistan. *Agronomy Journal* 49(3): 116–119.

Wakeel, A., Gul, M., Sanaullah, M., 2013. Potassium dynamics in three alluvial soils differing in clay contents. *Emirates Journal of Food and Agriculture* 25(1): 39–44.

Wang, M., Zheng, Q., Shen, Q., Guo. S., 2013. The critical role of potassium in plant stress response. *International Journal of Molecular Sciences* 14(4): 7370–7390.

Wubie, A.A., 2015. Review on Vertisol Management for the Improvement of Crop Productivity in Ethiopia. *Journal of Biology, Agriculture and Healthcare* 5(12): 92–103.

Zia-Ul-Hassan, Arshad, M., 2010. Cotton growth under potassium deficiency stress is influenced by photosynthetic apparatus and root system. *Pakistan Journal of Botany* 42(2): 917–925.

Zia-Ul-Hassan, Kubar, K.A., Rajpar, I., Shah, A.N., Tunio, S.D., Shah J.A., Maitlo, A.A., 2014. Evaluating potassium-use-efficiency of five cotton genotypes of Pakistan. *Pakistan Journal of Botany* 46(4): 1237–1242.

Zörb, C., Senbayram, M., Peiter, E., 2014. Potassium in agriculture – Status and perspectives. *Journal of Plant Physiology* 171(9): 656-669.