Response of crops to fertilizer application in volcanic soils

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Keywords: Potassium (K) has been considered as a non-deficient nutrient in most Ethiopian soils. However, some studies recommended K application to K sufficient soils if K/Mg ratio is < 0.7. To resolve this controversy, field experiments and laboratory soil analysis were conducted in two districts (Yilmana Densa and Dera) in north-western Ethiopia on Mollic Nitisols (aric, humic) (pH = 5.5), Pellic Vertisols (aric, gilgaic, mazic) (pH = 6.2) and Vertic Luvisols (aric, nitic) (pH = 5.2) using wheat, teff and maize, respectively as test crops. Field experiments were laid out in a randomized complete block design with 7 K fertilizer rates (0, 42, 83, 125, 166, 208, and 249 kg ha⁻¹) and four replications. KCl and DAP (200 kg ha⁻¹) fertilizers were added at planting. Urea (200 kg ha⁻¹) was added in split, half at planting and half at tillering for wheat and teff; and at knee-height stage for maize. Soil samples were taken two weeks after planting to determine K and Mg contents, K critical levels and optimum K/Mg ratio. The ammonium acetate extraction method was used to determine the K and Mg contents in the soil using a flame photometer and an atomic absorption spectrometer, respectively. Yield data were collected after harvest. The results of the study indicated that Mollic Nitisols (aric, humic), Pellic Vertisols (aric, gilgaic, mazic) and Vertic Luvisols (aric, nitic), had high K contents of 351, 380 and 434 mg kg⁻¹, respectively. Rising K fertilizer levels increased soil K contents; however, this did not significantly increase crop yields. Mg contents were also in high category (> 351 mg kg⁻¹). The K/Mg values ranged from 0.60 to 0.80 in Mollic Nitisols (aric, humic), 0.70 to 0.88 in Pellic Vertisols (aric, gilgaic, mazic) and 0.71 to 1.04 in Vertic Luvisols (aric, nitic), and the values increased with an increasing K rates. However, wheat, teff and maize grain yields showed an increasing trend up to K/Mg ratio of 0.71 in Mollic Nitisols (aric, humic), 0.78 in Pellic Vertisols (aric, gilgaic, mazic) and 0.88 in Vertic Luvisols (aric, nitic), respectively, and declined above these values.

1. Introduction

Potassium (K) is the third macronutrient that plays an important role in the activation of enzymes, photosynthesis, starch synthesis, nitrate reduction and sugar degradation (Askegaard et al., 2004). Adequate K nutrition improves the efficiency of the photosynthetic apparatus (Wang et al., 2004; Zou and Lu, 2010) and promotes plant roots (Hassan and Arshad, 2010). Potassium plays a remarkable role in transpiration, stomatal opening and closing and osmoregulation (Cakmak, 2005) and governs the degree of realization of yield potential (Behailu, 2017). Thus, its deficiency in the soil causes a serious reduction in crop yields because crops that encounter K deficiency become easily susceptible to diseases and pests. This susceptibility exposes them to damage by frost, and crops will have poor yield and quality (Umar and Moinuddin, 2001).

The fertilization of soils with volcanic rock powder, also known as a stonemel technique, can provide a large range of macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium and sulfur and micronutrients such as iron, manganese, copper, zinc and sodium, to the suitable plant growth (Linke et al., 2020; Silva et al., 2016; Sánchez-Peña et al., 2018; Ramos et al., 2017; Gómez et al., 2021; Oliveira et al., 2012). Potassium has been considered as an abundant nutrient in tropical soils as weathering of parent materials releases K to the soil (Sanchez, 1976). Murphy (1968), in his comprehensive work which is recognized as the first systematic approach in characterizing the nutrient status of Ethiopian soils, indicated that Ethiopian soils have adequate K. As a result, the use of potassium fertilizer on crop production in Ethiopia has not been prioritized for many years. Dawit and Reed (2002) also reported that dark clay soils (presumably Vertisols) and reddish-brown soils...
were located at 12°34′25″ north annual rainfall of 1100–1300 mm, high median temperature of 22°C, and altitude of 2000–2300 m above sea level. Mean temperature is 22°C, while relative humidity is 70% (Wassie, 2009; Wassie and Mekonnen, 2016). These were located at 12 National Regional State, north-western Ethiopia. The experimental sites located respectively in West Gojjam and South Gondar Zones, Amhara Regional State, north-western Ethiopia. This approach will improve the blanket K fertilizer recommendation given to farmers and optimize the costs associated with it.

Based on the above premises, ATA (2016) recommended K application to almost all soils of the Amhara Region with K/Mg ratio of <0.7. This recommendation was based on the work of Loide (2004), who suggested for the soils of Ethiopia with clayey texture. However, the determination of K/Mg ratio based on crop response field experiments has not been done so far. The aforementioned contradictory recommendations made the K deficiency issue to be unreasonable to some and plausible to others. Hence, in this study an attempt was made to assess the K, Mg and K/Mg status; evaluate the response of wheat, tef and maize to K application; identify the optimum K critical levels and K/Mg ratios for Mollic Nitisols (aric, humic), Pellic Vertisols (aric, gilgaic, mazic) and Vertic Luvisols (aric, nitic) of north-western Ethiopia. This approach will improve the blanket K fertilizer recommendation given to farmers and optimize the costs associated with it.

2. Materials and methods

2.1. Description of the study areas

The experiment was conducted on Mollic Nitisols (aric, humic) and Pellic Vertisols (aric, gilgaic, mazic) of Yilmana Densa and on and Vertic Luvisols (aric, nitic) of Dera districts (IUSW Working Group WRB, 2015) located respectively in West Gojjam and South Gondar Zones, Amhara Regional National State, north-western Ethiopia. The experimental sites were located at 12°48′40″-12°57′30″ N and 33°42′00″-34°14′00″ E in Yilmana Densa and 37°25′45″-37°54′10″ E longitude and 11°23′15″ -11°53′30″ N latitude in Dera districts. The altitudes in Yilmana Densa and Dera districts range from 1500-3500 and 1500-2600 m above sea level, respectively, with crop-livestock mixed farming system. Based on the climatic data (unpublished) obtained from the National Meteorological Agency, the study areas are characterized by a unimodal rainfall pattern with the main rainy season extending from June to September.

2.2. Field experiments

The field experiments conducted in 2017–18 cropping season had seven treatments (0, 42, 83, 125, 166, 208, and 249 kg ha–1 K as KCl) laid out in a randomized complete block design (RCBD) with four replications. All the K fertilizer was applied at planting. The KCl fertilizer was applied in broadcast method and mixed well with the soil just before planting, incubated for two weeks and then one composite soil sample (pulled from ten sub-samples) at the depth of 0–20 cm was collected from each treatment to evaluate soil available K, available Mg and K/Mg ratio. Basal doses of 92 kg N ha–1 nitrogen in the form of urea (46-0-0) and 46 kg P ha–1 phosphorus in the form of DAP (18-46-0) were applied to all treatments to avoid N and P limitations. All the DAP was applied at planting while urea was applied in split, half at planting and half at tillering for wheat and tef; and at knee-height stage for maize. The test crops were Taw variety of wheat (Triticum aestivum L.), Etsub (DZ-01-3186) variety of tef (Eragrostis tef [Zucc.] Trotter) and BH-540 variety of maize (Zea mays L.) for Mollic Nitisols (aric, humic), Pellic Vertisols (aric, gilgaic, mazic) and Vertic Luvisols (aric, nitic), respectively. Grain and above ground biomass yield data were used in this manuscript.

2.3. Laboratory analysis

Exchangeable K and Mg were determined after extracting the soil samples with 1N NH₄OAc solution at pH 7.0. Exchangeable K in the extract was measured using a flame photometer as outlined by Sahlemedihin and Taye (2000); while exchangeable Mg was analyzed using the atomic absorption spectrophotometer (Rowell, 1994). The exchangeable K and Mg (Cmol kg–1) values were converted to available K and Mg (mg kg–1) by multiplying the same by 390 and 120 (equivalent weight of the cations x 10), respectively. Similar analytical procedures were reported by several authors (Dalmora et al., 2016a, 2016b, 2020a, 2020b; Civeira et al., 2016). The soil samples were analyzed at the Soils Laboratory of Amhara Design and Supervision Works Enterprise.

2.4. Statistical analysis

Analysis of variance (ANOVA) was carried out using Statistical Analysis Software (SAS) version 9.0 (SAS, 2003) to evaluate the effect of fertilizer rates on crop yields. The Duncan Multiple Range Test (DMRT) at 5% levels of significance was used to separate the treatment means. The critical level of available K concentration was determined by Cate-Nelson graphical method (Cate and Nelson, 1965). The Cate Nelson method was used to plot the relative yield (0-100%) of wheat against the level of extractable K in the soil. Soil K-values were put on the X-axis and relative yield values (Relative grain yield (%) = yield/maximum yield *100) were put on the Y-axis. An attempt was made to divide the scatter points into four populations by positioning the horizontal and vertical lines to maximize the number of points in the positive quadrants and minimize the number of points in the negative quadrants. Then, the soil test value where the vertical line crosses the X-axis was selected as the soil critical level of extractable K concentration for the test crops. The maximum K/Mg values that give maximum grain yields (and beyond which the same will tend to decline) were calculated by equating the first order derivative (dy/dx) of the quadratic equation to zero and solving for x (Yihenew et al., 2003a, 2003b). The quadratic equations were developed by putting K/Mg values at the X-axis and grain yields (kg ha–1) at the Y-axis.

3. Results and discussion

3.1. Potassium and magnesium contents

Based on the laboratory analysis data of soil samples collected before fertilizer application, Mollic Nitisols (aric, humic), Pellic Vertisols (aric, gilgaic, mazic) and Vertic Luvisols (aric, nitic) had K content of 421, 427 and 532 mg kg–1, respectively. Hornrek et al. (2011) classified available K extracted by ammonium acetate method as low (<150), medium (150–250), high (250–800) and excessive (>800) mg kg–1. According to the same classification, the soils of the experimental sites fall in the ‘high’ category. Similarly, the recent evidence from soil map of the Amhara Regional State, north-western Ethiopia. This approach will improve the blanket K fertilizer recommendation given to farmers and optimize the costs associated with it.

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the soil Mg levels are rated as very low (1–50), low (51–150), medium (151–350), high (351–750) and very high (>750 mg kg\(^{-1}\)). Based on this classification, the soils of the study areas can be categorized as high. Similar to the soil K levels, Vertic Luvisols (aric, nitic) had the highest amount of Mg followed by Mollic Nitisols (aric, humic) and Pellic Vertisols (aric, gilgaic, mazic). However, the application of K fertilizer did not affect soil Mg contents except in Vertic Luvisols (aric, nitic). These results were generally in agreement with the maps of ATA (2016) developed for the districts that showed that K and Mg contents were optimum in many cases. K/Mg ranged from 0.60 to 1.04 and the values are well above the critical levels (0.70) based on ATA (2016) and Loide (2004). Increasing K fertilizer rates significantly (p < 0.05) increased K/Mg ratio for Mollic Nitisols (aric, humic) and Pellic Vertisols (aric, gilgaic, mazic) and highly significantly (p < 0.01) for Vertic Luvisols (aric, nitic).

### 3.2. Determination of K critical value

Use of adequate K level for optimum grain yield and maximum economic yield is possible only when soil test data are calibrated against the response curve for a given crop and soil type. To do this, the available K was put in the X-axis and the relative grain yield on the Y-axis (Cate and Nelson, 1965). However, it was not possible to overlay the horizontal and vertical lines to determine the critical levels. This was because of the absence of significant response of crop yields to K levels due to high inherent K contents (Figure 1). Based on the data available, the only thing

#### Table 1. Potassium and magnesium contents in the study soils.

|                     | Parameters               | Yilmana Densa District | Pellic Vertisols (aric, gilgaic, mazic) | Dera District |
|---------------------|--------------------------|------------------------|----------------------------------------|--------------|
| K rates             |                          | Av. K (mg kg\(^{-1}\)) | Av. Mg (mg kg\(^{-1}\)) | K/Mg ratio   | Av. K (mg kg\(^{-1}\)) | Av. Mg (mg kg\(^{-1}\)) | K/Mg ratio   | Av. K (mg kg\(^{-1}\)) | Av. Mg (mg kg\(^{-1}\)) | K/Mg ratio   |
| 0                   | 352c                     | 581                    | 0.61c                                  | 381c         | 539                    | 0.70c                                  | 434f         | 611c                    | 0.71cd                                  |
| 42                  | 393c                     | 631                    | 0.62c                                  | 340c         | 545                    | 0.73bc                                 | 517d         | 672a                    | 0.77c                                  |
| 83                  | 407abc                   | 648                    | 0.63c                                  | 418bc        | 587                    | 0.74bc                                 | 543c         | 659ab                   | 0.82b                                  |
| 125                 | 428ab                    | 641                    | 0.67bc                                 | 434b         | 580                    | 0.75bc                                 | 571b         | 650cd                   | 0.94ab                                 |
| 166                 | 442ab                    | 618                    | 0.72abc                                | 445ab        | 588                    | 0.76bc                                 | 588ab        | 592d                    | 0.99a                                  |
| 208                 | 456ab                    | 588                    | 0.78bc                                 | 447a         | 560                    | 0.80b                                  | 609a         | 585d                    | 1.04a                                  |
| 249                 | 470a                     | 581                    | 0.81c                                  | 468a         | 534                    | 0.88a                                  | 620a         | 585d                    | 1.04a                                  |
| p                   | *                        | ns                     | *                                      | ns           | *                      | *                                      | ns           | *                      | *                                      |
| Critical levels     | 250\(^1\)                | 151\(^2\)              | 0.70\(^3\)                             | 250\(^1\)    | 151\(^2\)              | 0.70\(^3\)                             | 250\(^1\)    | 151\(^2\)              | 0.70\(^3\)                             |

Mean values within a column followed by the same letter are not significantly different at \(P > 0.05\).

** = highly significant at \(P < 0.01\); * = Significant at \(P < 0.05\); ns = non-significant at \(P > 0.05\).

1 Horneck et al. (2011).
2 Benton (2003).
3 ATA (2016).

![Figure 1](image-url). Response of wheat, tef and maize to available K on Mollic Nitisols (aric, humic) (a), Pellic Vertisols (aric, gilgaic, mazic) (b) and Vertic Luvisols (aric, nitic) (c).
that can be concluded is that the K critical levels for wheat, tef and maize could be below 225, 375 and 450 mg kg\(^{-1}\) for Mollic Nitisols (aric, humic), Pellic Vertisols (aric, gilgaic, mazic) and Vertic Luvisols (aric, nitic), respectively. This result is supported by Horneck et al. (2011) who reported that K levels between 250 and 800 mg kg\(^{-1}\) are categorized as high. Based on the results of a pot experiment, Mulugeta et al. (2019) also reported K critical level of 210 mg kg\(^{-1}\) following the Mehlich-3 method (Mehlich, 1984) for tef to achieve 85% relative biomass yield level in Vertisols of Ethiopia. Other authors reported critical levels of 68 mg kg\(^{-1}\) in Tennessee, USA (Savoy, 2009) and 133 mg kg\(^{-1}\) in Uruguay (Barbazán et al., 2011).

The impossibility of determining the K critical levels was supported by the results of the field experiment that attempted to determine whether the crops respond to K fertilizer rates (Table 2). The result confirmed that there was no response of wheat, tef and maize to applied K on Mollic Nitisols (aric, humic), Pellic Vertisols (aric, gilgaic, mazic) and Vertic Luvisols (aric, nitic), respectively. Srinivas Rao et al. (2000) and Huu et al. (2017) reported that the application of an excessive amount of K can cause yield decline due to the antagonistic effect of the same on Mg. In contrast to this study, Mulugeta et al. (2020) reported a significant increase in tef grain and straw yields due to the application of K fertilizer in 67% of the tested locations covered by Vertisols. However, unlike the soils of the current study areas that had very high ammonium acetate extractable indigenous K levels (>352 mg kg\(^{-1}\)), the Mehlich-3 extractable available K (Mehlich, 1984) values were between 166 (low) and 282 (high) mg kg\(^{-1}\). Recent studies on Ethiopian soils (EthioSIS, 2013; ATA, 2014; ATA, 2016) 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, respectively. Similarly, Mulugeta et al. (2019) categorized Mehlich-3 K of <210, 210–280, 280–500 and 500 mg kg\(^{-1}\) as low, medium, high and very high, respectively.

### 3.3. Response of crop yield to K/Mg ratio

Ratios of nutrients in plant tissues have been widely used by many researchers in diagnosing mineral nutrient imbalances in crops (Sumner, 2009). Ratios of K/Mg were calculated for each soil type to examine the relationship between the K/Mg ratio and grain yield of wheat, tef and maize. The results showed that the K/Mg ratio had a linear relationship with the grain yield of the crops (Figure 2). The equations for the regression lines are as follows:

- Wheat:
  \[ y = -14427x^2 + 20724x - 3959 \]
  \[ R^2 = 0.876 \]

- Tef:
  \[ y = -6713x^2 + 10494x - 2388 \]
  \[ R^2 = 0.880 \]

- Maize:
  \[ y = -36173x^2 + 63555x - 20879 \]
  \[ R^2 = 0.876 \]

Table 2. Response of wheat, tef and maize to K fertilizer application in contrasting soils.

| K\(_2\)O rates | Yilmana Densa District | Dera District |
|---------------|------------------------|--------------|
|               | Mollic Nitisols (aric, humic) | Pellic Vertisols (aric, gilgaic, mazic) | Vertic Luvisols (aric, nitic) |
|               | Wheat grain yield (kg ha\(^{-1}\)) | Tef grain yield | Maize grain yield |
| 0             | 3293.49 | 7207.3 | 1666.15 | 1277.00 |
| 50            | 3349.13 | 7119.1 | 1687.48 | 1310.00 |
| 100           | 3388.99 | 7217.3 | 1701.59 | 1359.00 |
| 150           | 3463.09 | 7315.9 | 1720.84 | 1454.00 |
| 200           | 3448.12 | 7453.1 | 1715.69 | 1449.00 |
| 250           | 3457.18 | 7405.5 | 1698.32 | 1376.00 |
| 300           | 3349.10 | 7140.7 | 1650.52 | 1343.00 |
| Mean          | 3397.76 | 7265.6 | 1691.5 | 1366.9 |
| CV (%)        | 6.56 | 4.39 | 4.6 | 11.54 |
| p             | ns | ns | ns | ns |
| ns            | ns | ns | ns | ns |

NB: ABG = above ground biomass; CV = coefficient of variation; ns = non-significant at p > 0.05.
1978). Among the commonly encountered ratios in literature, K/Mg ratio is known for nutrient antagonism (Olaleye et al., 2009). Moreover, K can be fixed in the interlayer spaces of 2:1 clay minerals (smectites) containing soils like Vertisols (Brady and Weil, 2002) and the percentage increases with wetting and drying (Pose et al., 1991).

Therefore, an attempt was made to see how K/Mg affected crop yields. It was found that wheat yield could increase up to K/Mg of 0.71 for wheat, 0.78 for tef and 0.88 for maize on Mollic Nitisols (aric, humic), Pellic Vertisols (aric, gilgaic, mazic) and Vertic Luvisols (aric, nitic), respectively (Figure 2). This implies that maize demands more K than tef and wheat for the same level of Mg. The rise in K/Mg ratio above these values tended to diminish yield which could be due to K toxicity or K induced Mg deficiency that was indicated by Srivinas Rao et al. (2000) and Hsu et al. (2017). The basic justification for this is that K could be deficient in soils having a sufficient amount of the nutrient due to the availability of a disproportionate amount of cations like Mg that will suppress its uptake (Fanuel et al., 2016a, 2016b).

Loide (2004) and Leide (2001) suggested that K/Mg critical levels can be affected by soil texture. The author reported critical levels of 1.20 for sand soils, 1.10 for sandy loam soils, 0.70 for clay soils and 2.20 for peat soils. Fanuel et al. (2018) also reported ratio ranging from 0.20 to 1.60 for silty loam soils of Damot Gale district and 0.10 to 1.00 for clay textured soils of Damot Sore and Sodo Zuria districts, Southern Ethiopia. The same author used the K/Mg ratio of 0.70 (Loide, 2004; EthSIS, 2013) in classifying the soils as K nutrient demanding or not. According to the basic cation saturation ratio (BCSR) concept, maximum plant growth will be achieved only when the soil’s exchangeable Ca, Mg, and K concentrations are approximately 65% Ca, 10% Mg, and 5% K (Obasi et al., 2016). This result shows that the K/Mg ratio should be 0.50. Similarly, based on the Graham Model, a ratio of 0.50 is considered as an acceptable limit (Graham, 1959). As soils of the study are clay soils (Yihenew, 2002), the result of the current study are in line with these results. However, Obasi et al. (2016) reported K/Mg as low as 0.07 in rice soils of the Ebonyi area, Southern Nigeria.

4. Conclusions and recommendations

Based on the results of the study, it is concluded that K is not a limiting nutrient in the study areas because the soils of the study area have inherently high K levels that were evidenced by the non-response of crops to K application. K critical levels for wheat, tef and maize could be below 225.0, 375.0 and 450.0 mg kg⁻¹ for Mollic Nitisols (aric, humic), Pellic Vertisols (aric, gilgaic, mazic) and Vertic Luvisols (aric, nitic), respectively. K/Mg > 0.71 for wheat on Mollic Nitisols (aric, humic), >0.78 for tef on Pellic Vertisols (aric, gilgaic, mazic) and >0.88 for maize on Vertic Luvisols (aric, nitic) that increases from the application of K fertilizers could reduce crop yields. Further study including several soils that have K levels ranging from low to high is recommended to determine the critical levels.

Declarations

Author contribution statement

Yihenew G. Selassie: Conceived and designed the experiments; Wrote the paper.
Eyayu Molla: Conceived and designed the experiments.
Dinku Muhabie, Fentanesh Manaye, Demelash Dessie: Performed the experiments; Analyzed and interpreted the data.

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Data availability statement

Data included in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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