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Potassium dynamics under enset (*Ensete ventricosom cheesman)* farming systems of Sidama zone, Southern Ethiopia

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Potassium dynamics of soils is constituted by constantly changing relationship between soil K forms, and this relation is affected by some soil physical and chemical properties. Most Sidama (south Ethiopia) farmers grow enset crops which have high K requirements. The soils were collected from Awassa-Zuriya and Dale districts; 'Woinadega' (warm subtropical climate) and Hula district 'Dega' (wet, cool temperate climate). Overview of K dynamics in soils via Quantity-Intensity (Q/I) curves was used to evaluate the dynamics of K in fifteen soil samples representing the enset farming systems of Sidama. All of the Hula district soils and half of the Dale district soils had low percent K saturation. There were significant correlations between some soil properties and Q/I parameters and among equilibrium solution parameters and Q/I parameters. Variations among the mean quantity (±∆K) values of the soils were not significant. The Dale and Hula district soils had higher K intensity than the Awassa-Zuriya district soils; where the Hula (Adola kura kebele) soil had the highest value. Therefore, the Dale and Hula district soils will require frequent and split K applications since they have lower capacity to maintain long-term supply of K. On the other hand, Awassa-Zuriya district soils had high K quantity than the Dale and Hula district soils. This shows that the Awassa-Zuriya district soils have a higher potential to supply K for a longer period of time from the exchangeable pool. However, the Awassa-Zuriya district soils require less frequent and higher K fertilization to saturate the exchangeable pool to meet immediate potassium requirement of crops. The low equilibrium activity ratio of potassium and low potassium replenishing capacity of nearly all of the soils studied also indicated the need for K application.

Key words: Dynamics of potassium, potential buffering capacity, activity ratio, quantity-intensity isotherms, potassium saturation.

INTRODUCTION

Enset (*Enseteventricosum Cheesman*) is a part of sustainable production system and has been cultivated in Ethiopia since ancient times (Garedew et al., 2017). It is most commonly grown in home-gardens, frequently intercropped with peas or beans, which is suitable to compensate the low protein level in enset foods (Abebe

et al., 2010). It is also intercropped with cereal crops (maize, sorghum), root crop (sweet potato), coffee, cabbage, papaya and avocado.

Forms of soil potassium are partitioned into four different pools on the bases of the degree of availability to plants (Romheld and Kirkby, 2010). Among the pools the labile, soil solution and exchangeable K meet the immediate requirements of growing plants while the non-labile, non-exchangeable and mineral K are responsible for the long-term supply of K to plants (Askegaard et al., 2003).

Potassium dynamics in soils is described as the constantly changing relationship between labile and non-labile forms of K (Yawson et al., 2011). It helps to explain the movement of K in soil-solution-plant systems in relation to driving forces. Potassium dynamics depends on the magnitude of equilibrium among the K forms and it is mainly governed by the physicochemical properties of soils, mineral make up, exchange properties and rate of weathering (Lalitha and Dhakshinamoorthy, 2013). Constant change of K in soils is derived by gravitational and diffusion forces (Frissel, 1978). These forces cause dynamic equilibrium of K in soils and the dynamic equilibrium in turn distributes K into different forms. However, soil K forms and other soil properties are not homogeneously distributed in soils since the parent material, degree of weathering, K gains through manures and fertilizers and losses due to crop removal, erosion and leaching differs for different soils (Bogunovic et al., 2017; Rodrigo-Comino et al., 2017). In spite of this, farmers lack sufficient knowledge on soil conservation techniques and the importance of the soils in the bio-geological cycles (Biratu and Asmamaw, 2016; Cerdà et al., 2017).

So far, concentration of exchangeable K has been determined by traditional method that employs chemical extractants. However, Bansal et al. (2002) reported the insufficiency of exchangeable K alone for evaluating K availability under intensive cropping. This could be mainly due to the fact that dynamic interactions among different K pools control plant availability of soil potassium. As of late, new techniques that use adsorption isotherms and thermodynamic parameters such as ionic activity, activity coefficient, ionic strength, free energy of replacement, activity ratio and buffering capacity are considered by several researchers as accurate methods for evaluating potassium status and its availability in soils (Al-Zubaidi et al., 2008). These can be partly achieved through the study of the relationship that exists between changes in concentration of adsorbed K to changes in concentration of solution K; that is, Quantity/Intensity (Q/I) relationship

(Uddin et al., 2011).

Both intensity and soils inherent capacity to buffer K against changes are important parameters which determine availability of K to plants (Raheb and Heidari, 2012). Hence, misunderstanding of these dynamics leads to mismanagement of soil fertility. However, to assess the conditions of potassium uptake by plants, the extensive parameters such as potassium, calcium and magnesium contents of soils are also required (Yong-Hong, 2010). In this case, the activity ratio (AReK) described by Beckett (1964) is one of the satisfactory measures of the K dynamics and its availability, because it measures the chemical potential of labile K present to the chemical potential of labile calcium plus magnesium in the same soil.

To date, no research has been conducted and published on potassium dynamics in Sidama soils (south Ethiopia). The objective of this study was therefore to evaluate the dynamics of potassium under enset farming systems of Sidama, Southern Ethiopia and hence it was expected that the research will provide detailed information on the status of potassium.

MATERIALS AND METHODS

Study area

This study was conducted in Awassa-Zuriya, Dale and Hula districts of Sidama zone, Southern Ethiopia (Figure 1) in 2016. Sidama administrative zone is located within 5°45'- 6°45'N latitude and 38°-39°E longitude covering a total area of 6,538.17 square kilometers (SZPEDD, 2010). It lies in the area varying from flat land (warm to hot) to highland (warm to cold). The regional and zonal capital, Hawassa, which is located in the northern tip of Sidama zone, has a distance of 275 km from Addis Ababa (capital city of Ethiopia). Sample study areas (districts) from the zone were randomly selected because nearly all areas in the zone have good potential for *enset* production irrespective of productivity variation due to rainfall and altitude discrepancy. The selected districts are located between 38°20'7.8" - 38°32'36.5"E and 06°28'15.5" - 07°04'50.3"N. Awassa-Zuriya and Dale districts have moist to humid, warm subtropical climate with a mean annual precipitation of 1000 to 1800 mm, and have a mean annual temperature of 15 to 20°C. In these districts, perennial crops such as 'enset', 'chat' (catha edulis), coffee (*Coffea arabica), Avocado (Persea americana) and annual crops such as* maize (*Zea mays* L.)*,* tomato (*Solanum lycopersicum*), sweet potato (*Ipomea batatas*) and haricot bean (*Phaseolus vulgaris* L.) are widely grown. The Hula district has wet, cool temperate climate and receives an annual rainfall of 1200 to 1800 mm, and has the mean annual temperature of 10 to 15°C. In this district, enset (*Ensete ventricosum*), barley (*Hordeum vulgare*), bread wheat (*Triticum aestivum* L.), cabbage (*Brassica carinata*), and potato (*Solanum tuberosum*) are widely grown (SZPEDD, 2010).

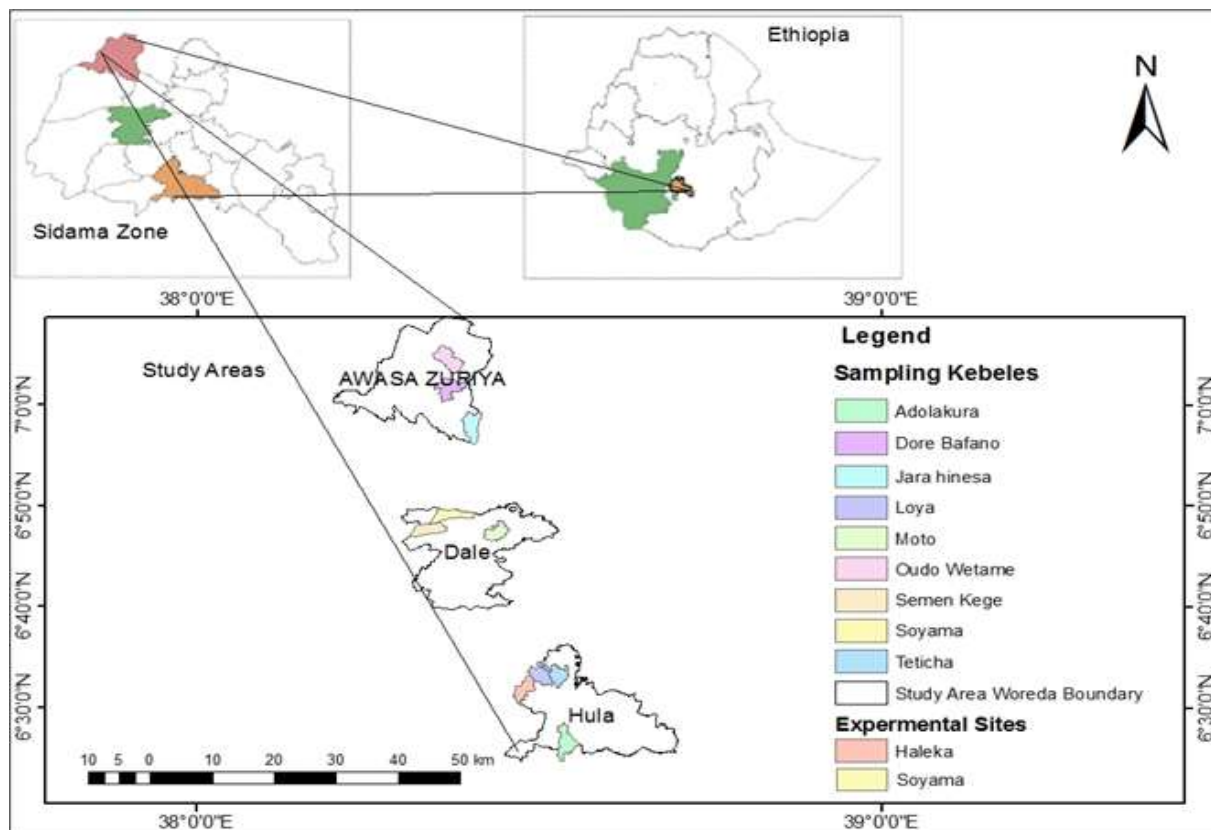*Corresponding author. E-mail: kibreselasiedaniel@yahoo.com

Figure 1. Location map of Sidama zone in Southern Ethiopia, study districts in Sidama zone and soil sampling kebeles in the study districts

Soil sampling

Forty five composite samples were collected in November, 2015 from the three randomly selected districts in Sidama zone where animal dung and manures fertilizers have been applied. After selecting representative farmers' *enset* farms in the farmer associations (kebeles), each field was divided into three stratum with 12 m long in the direction from home vicinity to far located fields. Composite soil sample (12 cores) from 50 cm depth was collected in a plastic pail from each stratum based on the method outlined in Hussen (2007) using auger. The soils were placed on a plastic sheet with an area of 3 m² and thoroughly mixed. About 1 kg sample was taken and kept in a polyethylene plastic bag and labeled. Before laboratory analysis, samples were air-dried at room temperature, ground using mortar and pestle, homogenized, and passed through a 2 mm sieve. Finally, samples were stored in clean and dry area at room temperature until the time of use.

Soil physical and chemical analysis

Selected physical and chemical properties of the soils were determined using standard procedures. The pH value was determined by 1:2.5 soil-water suspensions by a glass electrode (Jackson, 1973). Electrical conductivity was determined in supernatant solutions by electro conductivity meter. Organic carbon was determined by the wet oxidation method of Walkley-Black (1934). Cation exchange capacity (CEC) was determined by the 1N

NH_4OAc extraction method; and exchange acidity by the 1N KCl extraction method. Soil texture was determined by the hydrometer method (Bouyoucos, 1951) and the textural classes were determined using United State Department of Agriculture (USDA) soil textural triangle. Effective cation exchange capacity (ECEC) was determined by summation method. Lastly, the exchangeable potassium was determined using Mehlich III extractant (Mehlich, 1984).

Equilibration procedure

Soil samples selected were analyzed by the Quantity/Intensity procedure based on the method outlined in Beckett (1964). A stock solution of potassium chloride, 10 mmole/L KCl and Calcium chloride, 10 mmole/L $CaCl_2$ were prepared separately. From these separate solutions, graded concentrations of potassium (0.0, 0.2, 0.4, 1.0, and 2.0 mmol/L in 10 mmole/L $CaCl_2$) were prepared and used for equilibration study. From each soil samples, duplicates of 5 g soils were weighed and quantitatively transferred into each of five plastic tubes. Then, 50 ml of the graded concentration solutions from each was added to the correspondingly labeled plastic tubes. The suspensions were then shaken with a horizontal flask shaker for half an hour and allowed to equilibrate overnight. After equilibration, suspensions were filtered using Whatman No. 42 filter paper, and the equilibrium solutions were analyzed for potassium by Flame Photometer (BWB, 2012); for Electrical conductivity (EC)
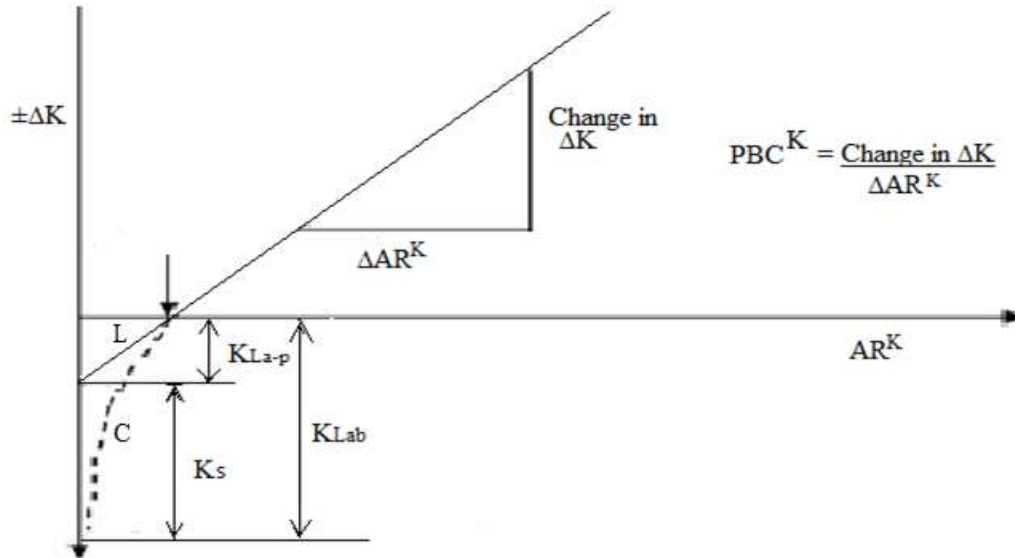
Figure 2. Typical Quantity/ Intensity plot.

by EC meter and for Ca and Mg by EDTA titration (Tucker and Kurtz, 1961).

Equations used to determine thermodynamic parameters and graphical analysis of Quantity/Intensity plots

Ionic strength (μ) mol/L in equilibrium solutions was calculated from the electrical conductivity (EC) using the equation.

$$\mu = 0.0129 * EC, \text{ (Lindsay, 1979).} \qquad (1)$$

Activities (a) of potassium, calcium and magnesium in equilibrium solutions were calculated as product of concentration of ions by their activity coefficient (γ) values. Activity coefficient of ions was calculated using extended Debye-Hückel equation:

$$\text{Log} \gamma = -AZi^2 \frac{\sqrt{\mu}}{1+Bdi\sqrt{\mu}} \qquad (2)$$

Where:
Zi: valency of ion
A: 0.508 for water at 25°C
B: 0.328×10^8 for water at 25°C
d: is the effective distance of closest approach measured in centimeter and corresponds roughly to the effective size of hydrated ions (d values for different ions are tabulated in Lindsay (1979)).

The gain (loss) of potassium in relation to the adsorbed phase (±ΔK) was calculated by measuring the corresponding increase or decrease in the concentration of potassium in the equilibrium solution, compared to the original solution using the following equation:

$$\Delta K = \text{Initial conc.} - \text{Final conc.} \qquad (3)$$

Where Initial conc. is K added and Final conc. is K in equilibrium solution.
The intensity (I) of labile K in the soil was determined by employing the formula of activity ratio of potassium to the sum of activities of calcium and magnesium in equilibrium solutions as:

$$AR^K = {}^a K \sqrt{a(Ca+Mg)} \text{ (Davis, 1962)} \qquad (4)$$

Where: a is activity

A graph of increase or decrease of K (on the y-axis) and the activity ratio of potassium (on the x-axis) were plotted. On this graph, the equilibrium activity ratio (AReK) was obtained by reading the value on the abscissa where increase or decrease of K (±ΔK) = 0 (Figure 2). 'L' and 'C' denote linear and curvilinear portions of the Q/I lines respectively. These were obtained by extrapolating from the lower x, y coordinate points to the y-axis. Non-specific K (K_{La-p}) was obtained from y-intercept of linear portion of the curve where AR^K = 0. Specific K (Ks) was obtained by extrapolating the linear portion of the curve to the ordinate, by drawing a tangent from the point of abscissa where ±ΔK = 0 and by measuring from the point of labile K (planar and non-specific K) to the end of tangent line on ordinate.
Potential buffering capacity was determined by calculating the slope of the linear portion of the curve. K-potential was determined by multiplying the non-specific potassium by the buffering capacity of potassium (PBC^K). The free energy or the potential of the soil for K-(Ca + Mg) replenishment was determined using the equation reported by woodruff (1955):

$$\Delta F = -2.303RT \log {}^a K \sqrt{a(Ca+Mg)} \qquad (5)$$

Where, T = Absolute temperature at 25°C (298K), R (universal gas constant), constant = 1.987 Cal/mol and a = activity of metal ions. Labile K ($-K_{lab}$) released by the soil was obtained graphically by extrapolating the linear portion of the Q/I plot to its y-intercept (Figure 2). Potassium saturation percentage was calculated using:

$$\%K = \frac{K_{ads}}{CEC} \times 100 \quad \text{(Mutscher, 1995)} \qquad (6)$$

Lastly, Potassium equilibrium parameters were computed with

Excel sheet facilities.

Statistical data analysis

Correlation analysis between soil properties and Quantity/Intensity parameters, between equilibrium solution parameters and Quantity/Intensity parameters were performed with the statistical analysis system (SAS Institute, 2012)

RESULTS AND DISCUSSION

Soil properties

The selected soils physico-chemical properties are presented in Table 1. The pHs of the soils were interpreted as per the ratings of EthioSIS (2014) and it ranged from 4.7 to 7.6, where neutral soils prevail. All of the Hula district soils were strongly acidic while 25% of the Dale district soils had moderately acidic reaction. The Awassa-Zuriya district soils were dominated with neutral and moderately alkaline pH ranges. These results are in line with the findings of David (2015) who suggested the effect of high exchangeable cations on the pH of soils. Organic carbon (OC) ranged from 1.2 to 4.1%. Based on Landon (2014), all soils of Awassa-Zuriya district were categorized as very low in OC while nearly all soils of the Dale and Hula districts had low level of OC. The result is in agreement with the findings of Laekemariam (2015) who reported low levels of OC in enset fields.

The mean particle size distribution in Awassa-Zuriya district is in the order of clay (35.67) > silt (34.67) > sand (29.33), whilst the distributions in Dale and Hula districts are in the order of clay (42) > sand (30.75) > silt (27.25) and sand (39.2) > clay (33.6) > silt (27.2), respectively. These values indicated that the Dale and Awassa-Zuriya district soils had relatively high clay fraction suggesting their ability to retain K than its loss through leaching. However, more K could be fixed in these areas. The Hula district soils, on the other hand, had relatively high sand fraction which aids leaching and the likelihood of acidic conditions than retention of K.

Based on Landon (2014), soils in all studied districts were sufficient in exchangeable Ca while closer values of exchangeable Mg content were found for all districts. Soils of Dale and Awassa-Zuriya districts had high amounts of soil exchangeable K while soils of Hula district had low amount (EthioSIS, 2014). There is a positive correlation between pH and ECEC and an inverse relation between pH and exchange acidity (Evangelou and Blevins, 1998). Consequently, considering the pH and the exchange acidity of Dale district Motto dorsiso. village, the high ECEC can be expected.

Potassium saturation percentage (%K) was found to range from 0.97 to 10.38 and had a mean of 4.28±3.0. Although the mean is above the critical, all soils of Hula district along with 50% of Dale district were found far below critical value of 2.3 (FAO-UNESCO, 1997). This indicated the saturation of CEC with other cations in these areas while on the contrary, all soils of Awassa-Zuriya district and half of the Dale district had potassium proportion of above the critical level.

Evaluation of equilibrium solution parameters

The mean values of parameters in the equilibrium solutions are presented in Table 2. In the table, the mean K^+ concentration in moles/L ranged from 1.06×10^{-4} (Awassa-Zuriya district, Oudo wetame village) to 6.41×10^{-4} (Hula district, Adola kura village). The Hula district, Adola kura, Teticha and Loya diko village soils had high K^+ concentrations and K activity. The Ca and Mg concentrations ranged from 0.644×10^{-2} to 2.073×10^{-2} moles/L and in the range, Awassa-Zuriya district, Oudo Wetame mote, Hula district Adola holo, Dale district, Soyama Bochesa, Moto gadelo and Moto gowe village soils had high values. On the contrary, the Hula district, Teticha and Adola kura village soils had low values. However, the activity coefficients for both [K^+] and [Ca^{2+}-Mg^{2+}] did not vary significantly; while the opposite can be said of the activity of both K and Ca-Mg. According to Affinnih et al. (2014), soil K^+ concentration can be used to assess the K status of soils.

K intensity

The availability of potassium is satisfactorily estimated from the activity ratio of K (AR^K) in a solution in equilibrium with a soil. Activity ratio (AR^K) is a measure of the intensity (I) of labile K in the soil and represents the K that is immediately available to crop roots. From Table 2, the mean values of AR^K ranged from 0.0008 to 0.0115 moles/L and increased with increasing concentrations of the equilibrating solutions. The range reported here is lower than those reported for some soils: 0.2231 to 0.5394 for Ghana soils (Yawson et al., 2011), 0.00174 to 0.0199 for Iran soils (Abaslou and Abtahi, 2008) and 0.0071 to 0.0320 for Egypt soils (Mahdy and Abu El-Eyuoon, 2017). Reason for these variations could be due to differences in the concentration of equilibrating solutions, equilibration time, the Ca and/or Mg contents and the differences in the mineralogy of the soils. Quantity/Intensity plots are presented in Table 4. In Table 4, Awassa-Zuriya district, Oudo Wetame mote village soil showed high value (-0.095 $(mol/L)^{1/2}$) of Planar K (easily exchangeable K or non-specific K) indicating the high release of K into soil solution. The lowest value, -0.0025.

K quantity

The quantity factor or gain/loss of K ($\pm\Delta K$) indicates

Table 1. Selected physical and chemical properties of the soils.

District	Village /Kebele/	pH	Organic Carbon (%)	Particle Size (%)				Exchangeable bases (cmolkg^{-1})				Exchange Acidity (cmolkg^{-1})	ECEC (cmolkg^{-1})	%K
				Clay	Silt	Sand	Textural Class	Ca	Mg	K	Na			
Awassa Z.	Jara hinesa	7.3	1.50	39	35	26	Clay loam	12.65	1.67	2.91	0.38	0.03	17.64	7.96
Awassa Z.	Oudo Wetame	7.5	1.92	39	45	14	Silty clay loam	20.44	3.34	1.75	0.45	0.02	26	6.45
Awassa Z.	Dore Bafano, diko	6.7	1.22	22	32	46	Loam	13.3	3.5	1.36	0.27	0.07	18.5	7.51
Awassa Z	Oudo Wetame, mote	7.0	1.71	46	34	20	Clay	20.34	5.26	1.07	0.27	0.06	27	6.69
Awassa Z.	Dore Bafano, dogo	6.2	1.37	48	32	20	Clay	15.08	4.93	1.60	0.29	0.10	22	10.38
Dale	Soyama, bochesa	7.1	1.69	20	30	50	Loam	22.16	7.06	1.56	0.18	0.04	31	5.50
Dale	Moto, dorsiso.	7.1	3.11	42	39	19	Clay	12.8	2.59	1.05	0.10	0.04	16.84	3.29
Dale	Moto, gadelo.	7.6	3.81	46	24	30	Clay	21.81	5.64	2.4	0.14	0.01	30	5.33
Dale	Moto, gowe	6.3	3.07	50	20	30	Clay	17.72	2.96	0.62	0.10	0.10	22.5	2.24
Dale	Semen Kege	7.2	2.20	30	26	44	Clay loam	17.27	3.17	1.66	0.12	0.05	22.27	2.28
Hula	Teticha	4.8	2.81	23	26	51	Sandy clay loam	17.08	5.09	0.34	0.15	0.12	22.72	0.97
Hula	Adola kura	4.9	4.12	19	40	41	Loam	11.4	4.49	0.37	0.11	0.17	16.54	1.26
Hula	Adola, holo	4.9	3.60	34	18	48	Sandy clay loam	18.78	4.99	0.47	0.14	0.11	24.49	1.47
Hula	Loya, diko	5.0	2.68	46	24	30	Clay	19	4.89	0.49	0.23	0.07	24.68	1.54
Hula	Loya	5.3	3.03	46	28	26	Clay	16.09	3.11	0.56	0.14	0.10	25	1.37

Awassa Z. = Awassa Zuriya

$$\%K \quad \frac{K_{ads}}{CEC} \quad X\,100$$

Table 2. Mean values of thermodynamic parameters of the equilibrium solutions.

District	Kebele	[K$^+$] ($\times 10^{-4}$) (mol/L)	[Ca + Mg] ($\times 10^{-2}$) (mol/L)	EC (dSm^{-1})	I ($\times 10^{-2}$) (mol/L)	γK	γ(Ca+ Mg)	$^aK^+$ ($\times 10^{-4}$)	^{a}(Ca^{2+}+Mg^{2+}) ($\times 10^{-2}$)	AR^K (mol/L)	$\pm\Delta$K ($\times 10^{-4}$) (mol/L)	ΔF (kj. mol^{-1})
Awassa Z.	Jara hinesa	3.42	1.50	0.097	0.1246	0.959	0.825	3.28	1.2334	0.0031	5.583	-15.72
Awassa Z.	Oudo Wetame	2.86	1.190	0.087	0.1117	0.962	0.833	2.75	0.9635	0.0029	6.141	-15.46
Awassa Z.	Dore Bafano, diko	1.40	1.992	0.062	0.0794	0.967	0.857	1.35	1.7078	0.0011	7.603	-18.20
Awassa Z	Oudo Wetame, mote	1.06	2.073	0.087	0.1117	0.962	0.820	1.02	1.7277	0.0008	7.936	-17.96
Awassa Z.	Dore Bafano, dogo	1.51	1.930	0.068	0.0880	0.966	0.830	1.45	1.6444	0.0012	7.494	-17.61
Dale	Soyama, bochesa	2.83	2.071	0.102	0.1313	0.958	0.850	2.72	1.6994	0.0021	6.167	-15.93
Dale	Moto, dorsiso	2.97	1.092	0.073	0.0945	0.965	0.846	2.86	0.9230	0.0031	6.032	-14.49

Table 2. Contd

Dale	Moto, gadelo	2.88	2.025	0.102	0.1313	0.958	0.821	2.76	1.6617	0.0022	6.115	-15.46
Dale	Moto, gowe	3.75	2.025	0.057	0.0730	0.970	0.869	3.65	1.7609	0.0028	5.252	-15.51
Dale	Semen Kege	3.95	1.400	0.067	0.0859	0.966	0.852	3.82	1.1931	0.0036	5.049	-14.96
Hula	Teticha	5.96	0.920	0.088	0.1138	0.961	0.832	5.73	0.7620	0.0062	3.038	-13.26
Hula	Adola kura	6.41	0.644	0.082	0.1052	0.963	0.838	6.17	0.5399	0.0115	2.590	-12.61
Hula	Adola, holo	3.55	2.033	0.057	0.0730	0.969	0.863	3.44	1.7547	0.0026	5.449	-15.47
Hula	Loya, diko	5.67	1.913	0.102	0.1313	0.958	0.821	5.44	1.5694	0.0044	3.327	-15.22
Hula	Loya	3.84	1.983	0.077	0.0988	0.964	0.842	3.70	1.6708	0.0030	5.160	-15.37

Awassa-Z = Awassa-Zuriya
$[K^+]$ = K concentration
AR^K = activity ratio of K
γK = activity coefficient of K
$[Ca + Mg]$ = Ca + Mg concentration
EC = Electrical conductivity
$^a(Ca^{2+} + Mg^{2+})$ = activity of Ca + Mg
$\pm\Delta K$ = gain/loss of K
$^aK^+$ = activity of K
I = Ionic Strength
$\gamma[Ca + Mg]$ = activity coefficient of Ca + Mg
ΔF = Free energy of replacement

the non-exchangeable and total elemental K reserves. It ranged from 0.000259 (Hula district Adola kura village) to 0.000794 moles/L (Awassa-Zuriya Oudo Wetame mote village). It was observed during the equilibration analysis that these values also increased with increasing concentrations of the equilibration solutions. Obviously, unlike the variation in intensity values (0.00329 ± 0.00265), the variation in the quantity values for the soils is not wide (0.000562 ± 0.000163). However, the range is lower than those reported for some soils: 1.3302 to 1.3327 for Ghana soils (Yawson et al., 2011), 0.001 to 0.0025 for Indian soils (Lalitha and Dhakshinamoorthy, 2015), and 0.00005 to 0.0031 for Poland soils (Bernard et al., 2006).

The free energy of replacement (ΔF)

The free energy of replacement that is used to determine the soils K supplying power was determined based on the method in Woodruff (1995) as shown in Table 4. In the table, soils whose ΔF value is lower than -14.7 kj.mol^{-1} are classified to have poor supplying power of potassium while soils whose ΔF ranges from -14.7 to -8.4 kj.mol^{-1} have medium supplying power. Lastly, soils whose ΔF value is less than –8.4 kj.mol^{-1} are classified as poor in replenishing potassium. Values obtained ranged from -18.2 to -12.61 kj.mol^{-1} and averaged to -15.55 ± 1.53 kj.mol^{-1}. This indicated that soils had poor supplying power of potassium and supplying

power varied from soil to soil due to variations in soils' mineralogical properties.

Parameters obtained from Graphical analysis of Q/I plots and their evaluation

The parameters obtained from evaluations of the(mol/L)$^{1/2}$ was determined in Dale district Moto dorsiso and Awassa-Zuriya district Oudo wetame villages indicating the soils' strong ability to absorb K. Moreover, examination of Quantity/ Intensity plots showed that soils of Awassa-Zuriya district, Jara hinesa, Dore Bafano and Dore Bafano diko; soil of Dale district, Semen Kege and soil of Hula district, Adola kura village have

Table 3. Classification of free energy of replacement (Source: Woodruff, 1995).

$\Delta F(kj.mol^{-1})$	Interpretation
Less than -14.7	Low supplying power of potassium
-14.7 to -8.4	Medium/marginal supplying power of potassium
Greater than -8.4	High supplying power of potassium

positive values (positive y-intercepts). The positive y-intercepts indicate the lack of planar K and strong ability of soils to absorb K. Due to this, K was not desorbed from the non-specific binding sites of these soils. Apart from these values, the rest soils have negative values of planar K indicating more K release into soil solution (Jalali, 2007).

Specific potassium (Ks) is the quantity of potassium held on specific edges or peripheral interstices of stacks of clay plates (Holzmueller et al., 2007). This potassium was determined by extrapolating quantity-intensity (Q/I) curves to the ordinates (Figure 2). Values of Ks ranged from -0.0005 to -0.044 (mol/L)$^{1/2}$ (Table 3). In the range, the lowest value was determined in Hula district Adola kura village soil, and Awassa-Zuriya district, Oudo Wetame mote village soil showed the highest. The highest Ks value in Awassa-Zuriya district could be due to high clay content (46%). On the contrary, the lowest Ks value of Hula district soil might be due to low clay content and high acidic reaction pH (4.7). Moreover, somewhat less from the highest Ks values were obtained in soils of Hula district Loya diko and Adola holo; in soils of Dale district Moto gadelo, Moto gowe and Moto dorsiso and in soils of Awassa-Zuriya district Dore Bafano diko and Oudo wetame mote villages. The Ks values of these soils also indicate high K fixing capacity that demands plants to apply more energy to take up potassium. On the other hand, the inverse can be said for soils with low Ks values in Awassa-Zuriya district Dore dogo and Jara hinessa, and in Dale district Semen Kege and in Hula district Adola kura villages.

Potential buffering capacity (PBC^K) expresses the ability of a soil to maintain a supply of K as crop use or leaching decreases the content of K in solution and is proportional to CEC. Although PBC^K often leads to low K intensity, a high value is indicative of greater capacity of the soil to maintain K for longer periods. On the other hand, soils having low PBC^K require frequent K fertilization since such soils fail to maintain a given supply of K for a considerable period of time (Wang et al., 2004).

The PBC^K values varied from 50 (Hula district Loya village) to 211 (Awassa-Zuriya district Oudo Wetame M. village (Table 4). According to Zharikova (2004), the values of PBC^K in cmol (p+) kg^{-1} were rated as very low (<20), low (21 to 50), medium (51 to 100), elevated (101 to 200) and high (> 200). Based on the rate, the Awassa-Zuriya district, Oudo Wetame, Dore Bafano diko, Dore

dogo, the Hula district, Adola holo, Teticha and the Dale district, Moto gadelo village soils had elevated buffering potential. On the other hand, soils of the Awassa-Zuriya district, Jara hinessa, the Hula district, Adola kura and Loya and the Dale district, Moto dorsiso, Moto gowe, Soyama bochessa and Semen Kege villages indicated medium buffering potential. On the contrary, soils of the Hula district, Loya diko and Awassa-Zuriya district, Oudo Wetame M. villages had low and high PBC^K, respectively. Soils PBC^K values of greater than 200 cmol(p+) kg^{-1} indicates the lowest percent K saturation (Zharikova, 2001).

According to Adinarayana et al. (1987), PBC^K correlates positively with ECEC. Hence, the high PBC^K of the Awassa-Zuriya Oudo Wetame mote village soil can be attributed to its high ECEC (Table 1) and a low activity coefficient of Ca-Mg (Table 2). Moreover, the elevated PBC^K of the Awassa-Zuriya district, Audo Wetame, Dore diko and Dore Bafano dogo, the Dale district, Moto gadelo, the Hula district, Adola holo and Teticha village soils could be attributed to their ECEC, high clay and Ca-Mg contents (Table 1). This suggests a preference for Ca-Mg over K adsorption (Schneider, 1997).

The equilibrium activity ratio (AReK) in (mol/L)$^{1/2}$, derived from the Q/I plots, ranged between 0.00001 (Awassa-Zuriya district Dore diko village) and 0.0013 (Dale district Moto gadelo village and Hula district Teticha village). This range is by far lower than the range obtained by Sharma et al. (2009), 0.00046 to 0.0213 (mol/L)$^{1/2}$ and the range obtained by Samadi (2012) for two different soil types, 0.0047 to 0.012 and 0.008 to 0.013 (mol/L)$^{1/2}$, which were reported as declined. However, the range of AReK in the present study is higher than the suggested minimum range 0.0005 (mol/L)$^{1/2}$ by Beckett and Webster (1971). Soils of Dale district, Moto gadelo, the Hula district, Loya and Teticha, the Awassa-Zuriya district, Oudo Wetame mote villages had relatively high AR$_e$K values and it could be attributed to their high percent organic carbon (Table 1). On the other hand, these soils had low percent K saturation since Ca$_{ex}$ and Mg$_{ex}$ concentrations influenced the overall potassium activity ratios (McLean and Watson, 1985). According to Fergus et al. (2005), in soil having low exchangeable K pool, the intensity (AReK) was reduced by the exhaustive cropping to 0.00047 (mol/L)$^{1/2}$. In the present study, about 73% of soils indicated AReK values of lower than this minimum. On the contrary, soils of Dale

Table 4. Parameters determined by evaluating Q/I plots.

District	Kebele	AReK	K_{La-p}	$-K_S$	PBC^K	K- Potential
Awassa-Zuriya	Jara hinesa	0.00007	+0.022	-0.004	57	-----
Awassa-Zuriya	Oudo wetame	0.00010	-0.0025	-0.019	111	-0.28
Awassa-Zuriya	Dore Bafano, diko	0.00001	+0.009	-0.002	157	-----
Awassa-Zuriya	Oudo Wetame, mote	0.00042	-0.095	-0.044	211	-20.1
Awassa-Zuriya	Dore Bafano, dogo	0.00015	+0.0003	-0.037	157	-----
Dale	Soyama, bochesa	0.00053	-0.021	-0.029	100	-2.10
Dale	Moto, dorsiso.	0.00020	-0.0025	-0.034	73	-0.18
Dale	Moto, gadelo.	0.00130	-0.093	-0.038	180	-16.7
Dale	Moto, gowe	0.00012	-0.0029	-0.036	100	-0.29
Dale	Semen Kege	0.00010	+0.008	-0.004	60	------
Hula	Teticha	0.00126	-0.0083	-0.016	125	-1.04
Hula	Adola kura	0.00025	+0.0048	-0.0005	92	------
Hula	Adola, holo	0.00020	-0.0051	-0.033	114	-0.58
Hula	Loya, diko	0.00030	-0.0068	-0.035	100	-0.68
Hula	Loya	0.00080	-0.0085	-0.021	50	-0.43

+ = Positive y-intercepts,
AR_eK = equilibrium activity ratio of K (mol/L)$^{1/2}$,
K_{Lab} = Labile K (cmol (P+) Kg^{-1}),
PBC^K = Potential buffering capacity (cmol(P+) Kg^{-1} mol$^{1/2}$/L$^{1/2}$,
K_{La-p} = Non-specific K (cmol (P+) kg^{-1}
K-Potential = [(cmol (P+) kg^{-1})mol$^{-1/2}$L$^{1/2}$]
$-K_s$ = Specific K (cmol (P+) kg^{-1}).

district, Moto gadelo, Hula district, Teticha and Loya and Awassa-Zuriya district, Oudo wetame mote had high values of K intensity. This shows greater tendency to maintain K supply to crops though K could be lost through leaching.

The K-potential is the product of non-specific K and PBC^K and it indicates K availability in soil solution. From Table 4, the Awassa-Zuriya district Oudo Wetame mote village soil had the highest K-potential and Ks while the Dale district Moto dorsiso village soil showed the lowest K-potential. This confirmed the soil's lower preference for specific adsorption of K. Soils of Hula district, Adola kura, Dale district, Semen Kege and Awassa-Zuriya district, Jarra hinesa, Dore Bafano diko and Dore Bafano dogo villages, had no K-potential but low Ks values. In these soils, more K may be fixed at specific adsorption sites and creates a lower PBC^K on equilibration (Abaslou and Abtahi, 2008). On the other hand, soils of Awassa-Zuriya district, Audo Wetame mote and Dale district, Moto gadelo villages had high K-potential and Ks. These soils release more K from non-specific (planar) sites, leading to higher PBC^K on equilibration. A cross-correlations between the soil properties and the Q/I parameters are presented in Table 5.

From Table 5, AReK shows intermediate positive correlation with ECEC. This is expected since ECEC of soils plays a positive role on the availability of plant nutrients. Potential buffering capacity indicates intermediate positive correlation only with Mg$_{ex}$. K-potential shows intermediate negative relationships with Ca$_{ex}$ and ECEC while intermediate positive relationships existed with pH. This could be due to high concentration of Ca in solution which prevented K from desorbing into soil solution and the same explanation can be given for the relation with ECEC (Diatta et al., 2006). Non-specific K shows intermediate negative correlations with Ca$_{ex}$ and ECEC. Since non-specific K represents K desorbed from the exchangeable pool, high concentration of Ca$_{ex}$ in soil solution and high ECEC might reduce the extent of K desorption. Specific K shows intermediate negative correlations with Clay, Ca$_{ex}$ and ECEC. This is very convincing that K desorption from specific sites is lowered as clay percent increases and the same can be suggested for Ca$_{ex}$ and ECEC. Finally, free energy shows an intermediate positive relationship with only organic carbon. This indirectly agrees with Talibudeen (1972) who pointed out the dependence of free energy on CEC which in turn depends on soil organic matter. Lastly, no significant relationships were found among the rest of the soil properties and the Q/I parameters.

In Table 6, the results of cross-correlation among equilibrium solution parameters and Q/I parameters are presented. In the table, strong positive correlations were found among [K$^+$], ^aK, AR^K and ΔF. Such associations existed because these parameters explain K status in equilibrium solution. On the other hand, PBC^K shows

Table 5. Cross-correlation among soil properties and Q/I parameters.

Parameter	AR_eK	K_{La-p}	Ks	PBC^K	K-Potential	ΔF
Ph	-0.0605	-0.4613	-0.1502	0.0670	-0.4355	-0.3952
Organic Carbon	0.3943	-0.0950	-0.1198	-0.1774	-0.0569	0.7174***
Clay	0.0885	-0.2279	-0.6583**	0.1271	-0.2685	-0.3168
Silt	-0.3165	0.0015	0.0818	0.0255	-0.0312	-0.2914
Sand	0.2284	-0.3200	0.4609	-0.1449	-0.4601	0.2514
Ca_{ex}	0.4808	-0.5655*	-0.5391*	0.2369	-0.5135*	-0.1994
Mg_{ex}	0.4553	-0.4696	-0.4337	0.5501*	-0.4502	-0.0722
K_{ex}	-0.1001	-0.2345	0.1397	0.0707	-0.2231	-0.3565
Exchange acidity	-0.0050	0.4341	0.1904	-0.0843	0.3999	0.3689
ECEC	0.5010*	-0.5959*	-0.5596*	0.3737	-0.5286*	-0.2356

* Significant at $P < 0.05$; ** at $P < 0.01$; *** at $P < 0.005$.

intermediate negative associations with [a]K and [K$^+$]. This indicates that soils K buffering capacity declines as exchangeable K desorbs while equilibrium K content increases. In agreement to this, $\pm\Delta K$ correlated positively and intermediately with PBC^K. Equilibrium K [K$^+$] indicates perfect negative correlation with $\pm\Delta K$. This shows inverse relation since complete increase in the amount of adsorbed K is accompanied by complete decrease in equilibrium K concentration. Moreover, intermediate positive correlations occurred between Ks and K_{La-p}, and K-potential and Ks. From this it can be said that Ks is directly proportionate to K_{La-p} and the same can be said for K-potential and Ks. Furthermore, K-potential shows intermediate negative correlation with PBC^K. This indicates the decrease of soils K buffering potential as crop available K increases. Lastly, AR_eK shows intermediate negative correlation with K_{La-p} though unexpected.

Conclusion

So far, the evaluation of soil potassium in terms of its availability to crops has been based on the figure obtained using chemical extractants. The problems are however weak correlations found between this K-pool and crop yields. Therefore, identifying, quantifying and monitoring soil properties and K changes are necessary to prevent soil degradation. Supporting this fact, growing researches on this issue are indicating that Quantity-Intensity (Q/I) isotherms provide a better estimation of plant available potassium. Due to this, Quantity/Intensity isotherms were used to evaluate the K dynamics in fifteen selected soils with varying properties representing the enset farm systems of Sidama, south Ethiopia.

It was believed that high silt proportion at Awassa-Zuriya district could increased the K adsorption capacity of soils. The higher K ratio (intensity) at Dale and Hula districts obtained while high quantity is measured at Awassa-Zuriya district soils shows that, Awassa-Zuriya district soils have a higher potential to supply K for a longer period of time from the exchangeable pool. On the other hand, the Dale and Hula soils will have high K concentration in solution immediately after K fertilization. Nevertheless, this high K intensity can be rapidly depleted through leaching and/or plant uptake. Moreover, According to the results of previous findings, higher K$^+$ intensity and activity lead to a lower PBC^K which is a better indicator of the ability of soil to maintain K intensity. Consequently, the Dale and Hula district soils which had higher K intensity will have lower PBC^K. Moreover, the Hula and Dale district soils had low potassium saturation. Therefore, the Dale and Hula district soils will require split and frequent K fertilization. On the other hand, the low free energy of replacement values determined indicated poor capacity of soils to supply K with minor exception. This also pointed out that the studied areas require K fertilization to boost crop production.

From the graphical analysis of Quantity/intensity plots, nil K-potential was determined for half of the Awassa-Zuriya district samples while low AReK values obtained nearly for all samples. This also pointed out the need for K application in Awassa-Zuriya district. Furthermore, indirect and direct associations existed between soil physico-chemical properties and the Q/I parameters further illuminated light on the behavior of K in soils and simplified the evaluation of its dynamics.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Table 6. Cross-correlation among the equilibrium solution parameters and Q/I parameters.

Parameter	[K$^+$]	^{a}K$^+$	AR^K	±ΔK	AR$_e$K	K$_{La-p}$	Ks	PBC^K	K-Potential	ΔF
[K$^+$]	1									
^{a}K$^+$	0.9999*****	1								
AR^K	0.8575*****	0.8571*****	1							
±ΔK	-1*****	-0.9999*****	-0.8573*****	1						
AR$_e$K	0.2572	0.2540	0.1101	-0.2582	1					
K$_{La-p}$	0.3651	0.3677	0.3073	-0.3637	-0.5276*	1				
Ks	0.3346	0.3342	0.4845	-0.3338	-0.2186	0.5205*	1			
PBC^K	- 0.5124*	-0.5144*	-0.3586	0.5117*	0.2261	-0.7041***	-0.4593	1		
K-Potential	0.3908	0.3932	0.3048	-0.3896	-0.4558	0.9921*****	0.5021*	-0.7306***	1	
ΔF	0.8915*****	0.8919*****	0.8461*****	-0.8915*****	0.3068	0.2957	0.3062	-0.5467*	0.3281	1

*Significant at $P < 0.05$; ** at $P < 0.01$; *** at $P < 0.005$; ****at $P < 0.001$; ***** at $P < 0.0001$.

devotion to support food insecure society through very indispensible and timely researches on potassium status of soils.

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