Potassium Fractions and Release from Mineral Sources of Potassium as Influenced by Potassium Solubilizing Bacteria (*Bacillus sporothermodurans*)

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Authors' contributions

Original Research Article

ABSTRACT

Potassium (K) in soil exists in four different forms such as water soluble, available, exchangeable and non-exchangeable potassium. Variation in K fractions in soils through addition of different mineral sources of K is essential to determine suitable mineral source for crops. A laboratory incubation study was conducted using seven mineral sources of K such as sulphate of potash, langbeinite, sylvinite, kainite, patentkali, glauconite and rockdust for a period of 180 days to evaluate the release pattern of different K fractions with and without adding potassium solubilizing bacteria (*Bacillus sporothermodurans*). The results revealed that potassium fractions varied significantly with the mineral sources. The water soluble (86.00 kg ha^{-1} to 268.90 kg ha^{-1}) and available K (144.60 kg ha^{-1} to 326.75 kg ha^{-1}) were increased gradually while non-exchangeable

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potassium (59.95 kg ha^{-1} to 221.10 kg ha^{-1}) showed a gradual decrease in content when potassium solubilizing bacteria added. But there was a corresponding decrease and increase in these fractions from 120 days of incubation when mineral sources alone were added. The highest water soluble and available potassium recorded in treatment received sulphate of potash and langbeinite with and without potassium solubilizing bacteria. The exchangeable K (45.20 kg ha^{-1} to 137.40 kg ha^{-1}) recorded the highest content in treatment received sylvinite. HNO$_3$ extractable K (353.80 kg ha^{-1} to 389.55 kg ha^{-1}) was highest in treatment received sulphate of potash and only a slight variation was observed during incubation period. When analysing the release of K from mineral sources it can be concluded that sulphate of potash and langbeinite having more available form of K whereas sylvinite contain more K as exchangeable form. In rock dust and glauconite non-exchangeable form of K was dominating. Potassium solubilizing bacteria converted the non-exchangeable form to available form in all mineral sources of K.

Keywords: Potassium fractions; release; mineral sources; water soluble K; available K; exchangeable K; Non-exchangeable K; potassium solubilizing bacteria.

1. INTRODUCTION

Potassium is an essential, major plant nutrient with numerous functions of activating about sixty enzymes, regulating stomatal function, controlling water relations especially under rainfed crop production, influencing the water balance of the plant system, and underpinning agronomic productivity and sustainability [1]. K is also the most abundant nutrient element in the earth's crust and it accounts for 2.6 per cent of the weight of earth's crust which is more than phosphorus which weighs only 0.1 per cent and nitrogen is only present in trace amounts [2].

Plants often absorb a large amount of potassium equal to or greater than nitrogen, which has drawn attention to study the behaviour of potassium in soil. Usually nitrogen and phosphorus are more concerned than K which is an important nutrient determining the yield of a crop. A thorough understanding of potassium status in the soil could be possible only by measurement of its different forms in the soil solution and the solid phase of soil.

Potassium exist in soil in different forms *viz.,* water soluble, available, exchangeable, and non-exchangeable K. But these forms were not homogeneously distributed in soils. Its amount in soil depends on the parent material, degree of weathering, K gains through manures and fertilizers and losses due to crop removal, erosion and leaching. A recent report of an incubation study revealed that K fertilization combined with straw incorporation results in alteration of K fractions and availability in soil [3]. As rocks break down into sand, silt and clay, that will enrich the soil with potassium and other nutrient elements by releasing and became available to plants. Water soluble K is directly taken up by plants and microbes which is most subjected to leaching loss. The content of water soluble K is generally low, unless external source of K have been added to the soil. Exchangeable K is the portion of the soil K that is electrostatically bound as an outersphere complex to the surfaces of clay minerals and humic substances. It is readily exchanged with other cations and also available to plants. Non-exchangeable K is held between adjacent tetrahedral layers of dioctahedral and trioctahedral micas, vermiculites and intergraded clay minerals such as chloritized vermiculite. There is one more form of K that is mineral potassium in which K bonded within the crystal structure of K-bearing primary minerals such as muscovite, biotite and feldspars [4].

Under conventional cropping systems, a large amount of K is being removed, leading to serious depletion of soil K reserves [5]. In order to overcome the problem of K deficiency in soil, supplementing external input during crop cultivation is necessary with mineral sources of potassium like glauconite, sulphate of potash (SOP), langbeinite, sylvinite, patenkali and kainite [6] which are capable of meeting the potassium requirement of crops and are potential sources K especially under organic cultivation. Glauconite is a micaceous mineral containing K, Fe and Mg, as well as Al and Si and the chemical formula is (K, Na)(Fe(III),Al, Mg)$_2$(SiAl)$_4$O$_{10}$(OH)$_2$ [7]. SOP is generally contains K (40 per cent) and S (17 per cent). Langbeinite is a potassium magnesium sulphate mineral with the chemical formula K$_2$Mg$_2$(SO$_4$)$_3$. It provides a readily available supply of potassium (K), magnesium (Mg) and sulphur (S). Sylvinite is a sedimentary rock made of a mechanical mixture of the

minerals sylvite (KCl or potassium chloride) and halite (NaCl or sodium chloride). Patentkali is chemically sulphate of potash containing magnesium salt having 30 per cent K_2O, 10 per cent MgO and 42.5 per cent SO_3 [8]. Kainite is one of the naturally occurring sources of potassium. It is a double salt of hydrated potassium and magnesium sulphate chloride ($KMgSO_4Cl \cdot 3H_2O$).

The mineral sources of K not only contain K but they also have other nutrients in some extent. The presence of other nutrients may affect the K availability in the soil. A recent incubation study on potassium mineralisation under different phosphorus level explained the effect of P on K mineralization. It initially found to be slowing down and a rapid increase was observed up to 90 days and then again slowed down [9].

Potassium solubilizing microbes (KSM) is a group of micro-organisms playing a key role in the natural K cycle. It solubilizes the unavailable form of K into available form of K through mechanisms such as acidolysis, chelation, complexolysis, exchange reactions and production of organic acids [10]. In soil the amounts of non-exchangeable K present are high as compared to water soluble and exchangeable K [11]. The application of KSM is effective in utilization of the unavailable forms of K such as non-exchangeable K. Hence a study was conducted to evaluate the release pattern of various K fractions in soil when applied with the organic mineral sources alone and along with KSM.

2. MATERIALS AND METHODS

A laboratory incubation experiment was conducted in College of Agriculture, Vellayani, Thiruvananthapuram, Kerala Agricultural University during 2020-21 to study the potassium release pattern from mineral sources of K alone and with potassium solubilizing bacteria (*Bacillus sporothermodurans*). The selected mineral sources of K were sulphate of potash, patentkali, sylvinite, langbeinite, kainite, glauconite and rock dust. Five kilograms of soil was taken in pots and the selected organic mineral potassium sources were added to the pots by thorough mixing at the rate of 75 Kg K_2O per ha. The moisture in pots was maintained at field capacity. The study was laid out in completely randomized design (CRD) with fifteen treatments and two replications *viz.,* soil alone (T_0), sulphate of potash 75 kg ha^{-1} + 5 kg soil (T_1), patentkali 75 kg ha^{-1} + 5 kg soil (T_2),

sylvinite 75 kg ha^{-1} + 5 kg soil (T_3), langbeinite 75 kg ha^{-1} + 5 kg soil (T_4), kainite 75 kg ha^{-1} + 5 kg soil (T_5), glauconite 75 kg ha^{-1} + 5 kg soil (T_6), rock dust 75 kg ha^{-1} + 5 kg soil (T_7), sulphate of potash 75 kg ha^{-1} + 5 kg soil + potash solubilizing bacteria 2kg ha^{-1} (T_8), patentkali 75 kg ha^{-1} + 5 kg soil + potash solubilizing bacteria 2kg ha^{-1} (T_9), sylvinite 75 kg ha^{-1} + 5 kg soil + potash solubilizing bacteria 2kg ha^{-1} (T_{10}), langbeinite 75 kg ha^{-1} + 5 kg soil + potash solubilizing bacteria 2kg ha^{-1} (T_{11}), kainite 75 kg ha^{-1} + 5 kg soil + potash solubilizing bacteria 2kg ha^{-1} (T_{12}), glauconite 75 kg ha^{-1} + 5 kg soil + potash solubilizing bacteria 2kg ha^{-1} (T_{13}), rock dust 75 kg ha^{-1} + 5 kg soil + potash solubilizing bacteria 2kg ha^{-1} (T_{14}).

Soil samples were collected from the pots on 0, 15, 30, 45, 60, 90, 120, 150 and 180 days after application of treatments, air dried in shade, ground using wooden pestle and mortar and sieved through 2 mm sieve and analysed for K fractions *viz:* Water soluble K, available K, Exchangeable K, HNO_3 extractable K and non-exchangeable K.

Water soluble K was estimated by extraction with distilled water (Soil water ratio 1:5) and the potassium in the extract was determined by flame photometer [12]. Available K was determined by extracting soil with neutral normal ammonium acetate solution (1 N) in a ratio of 1:2.5 and K content in the extract was determined by flame photometry [12]. Exchangeable K was computed as the difference between available K and water soluble K. The boiling 1N HNO_3 method [13] was followed for the determination of HNO_3 extractable K in soil. The soil acid ratio is 1:10 and the potassium content in the extract was determined using flame photometer. Non-exchangeable K was estimated by subtracting available K from HNO_3 extractable K.

3. RESULTS AND DISCUSSION

3.1 Water Soluble K

The water soluble K content (Table 1) varied from 22.85 to 268.90 kg ha^{-1} from 0 day to 180 days of incubation. The highest amount of K was released in treatments T_8 (268.90 kg ha^{-1}) and T_1 (248.25 kg ha^{-1}) which received sulphate of potash along with KSB and SOP application only at 180th and 120th day of observations respectively. The release of water soluble K was found to increase in all treatments up to 120

days. After 120 days the treatments which received the minerals alone were found to decrease the water soluble K content except glauconite and rock dust. In the case of glauconite and rock dust an increase was found up to 150 days and then decreased. Application of mineral sources along with the KSB gradually increased the water soluble K content up to 180 days of incubation.

The increased release of water soluble K fraction may be due to the increased solubility of all the minerals in water. The water soluble K content in soil depends on the moisture content and its concentration found maximum at field capacity [14]. Above field capacity the K ions may be subjected to leaching. A decrease in the K content in the treatments receiving minerals alone was recorded after 120 days of incubation. This may be due to the reversible reaction occurring to maintain the equilibrium between the K fractions. All the K forms in the soil are in dynamic equilibrium with each other that affects the level of water soluble K [15]. A gradual increase of water soluble K observed in treatments receiving minerals along with KSB throughout the incubation period. This may be due to the activity of the K solubilizing microbes in the inoculum which quickly dissolve minerals and chelate silicon ions, releasing K ions into the soil to make potassium available from unavailable forms [16].

3.2 Available K

The available K content (Table 2) was increasing gradually up to 90 days and thereafter a decrease in available K content was observed in treatments receiving minerals alone. The highest available K was recorded by the treatment T_8 (326.75 kg ha^{-1}) which received SOP along with KSB and the lowest content was recorded by kainite (144.60 kg ha^{-1}) at 1st day of incubation. The pattern of K release from the mineral sources indicating that, sulphate of potash released the available K rapidly into the soil followed by langbeinite. Treatment T_8 had the highest K content throughout the incubation period followed by T_1 (SOP), T_4 (langbeinite) and T_{11} (langbeinite+KSB). Sylvinite, patentkali and kainite were released K relatively slow when compared to SOP and langbeinite even though they were having more K content. Glauconite and rock dust were also released K very slowly.

The increase in available K observed would be due to the fraction that contributed by the release of K$^+$ ions from the K minerals as well as the soil clay minerals. The water soluble fraction from K mineral, if it was neither absorbed by the plant nor subjected to leaching get converted into exchangeable form. These could be the reasons for increase in available K at initial stages [17]. In treatments receiving K minerals along with KSB showed an increase in available K may be due to the presence of K solubilizing microbes which play a key role in the natural K cycle. It solubilizes the unavailable form of K (i.e., Non-exchangeable K, lattice K and mineral K) into available form of K [10]. The decrease in available K in treatments receiving only minerals may be due to the dynamic equilibrium maintained between the K forms in soil [14].

3.3 Exchangeable K

The data on exchangeable K revealed that the highest mean value of exchangeable K was recorded at 0th day in all treatments. After that it was found to be exhibiting a wide variation throughout the incubation period (Fig.1). More amount of exchangeable K content was observed in treatment T_0 (soil alone) at 15th day (132.35 kg ha^{-1}) and 30th day (137.40 kg ha^{-1}) followed by treatment T_3 (sylvinite). It was also statistically on par with T_3 at 30th day of observation (135.10 kg ha^{-1}). From 45 days onwards the highest exchangeable K content was recorded by the treatment T_{10} (sylvinite+KSB) which was statistically on par with treatments T_{13} (glauconite+KSB), T_3 (sylvinite) and T_7 (rock dust) on 120th day's observation.

Exchangeable K is the portion of the soil K that is electrostatically bound as an outer sphere complex to the surfaces of clay minerals and humic substances. It is readily exchanged with other cations and also is readily available to plants [2]. The increase in exchangeable K content may be observed due to more K$^+$ ions are adsorbed on clay surface. The reaction rate between soil solution and exchangeable phases of K is strongly dependent on the type of clay minerals present [15]. The decrease in K content may be due to release of K from the clay surface to soil solution. The decrease in the K concentration in soil solution triggers the release of K from the exchangeable K fractions [14]. The interaction between the clay content and K concentration in various K minerals showed a significant effect on the exchangeable K content. This may be attributed to the difference in

releasing and fixing capacity of different clay minerals present in the soil because the exchangeable K is found with different bond strength at the various sites of clay minerals [17] which was in agreement with the study of transformation of applied K fertilizer in soil. Recently, it has been reported that the presence of specific clay minerals affect the K-fixing capacity and slow and fast release of K in different soils [18].

3.4 HNO_3 Extractable K

The HNO_3 extractable K content (Table 3) in soil recorded an increase in trend up to 45th day of incubation and thereafter showed a decline in tendency during the incubation period. After 45th day there was a decrease in K content was recorded and gradual decrease was observed in all treatment receiving KSB. The treatments receiving K minerals only were showed an increase in K content at last stages of incubation. The highest HNO_3 extractable K content was recorded in treatment T_1 (sulphate of potash) on 180th day of incubation (389.55 kg ha^{-1}). The lowest value was registered in treatment T_{14}

(rock dust + KSB) on 180th day of incubation (353.80 kg ha^{-1}).

The treatments was found insignificant on 0th day of incubation which indicates that the addition of K from a mineral or fertilizer source did not have any immediate change in the HNO_3 extractable or fixed K. The initial rise in the HNO_3 extractable K in different treatments may be due to conversion of excess exchangeable K content to the slowly available form. When K is applied in soil, there will be the inter-conversion of different forms of K in order to maintain to maintain the equilibrium level [19]. There was a decrease in K content was observed after 45th day with corresponding increase in water soluble and exchangeable fraction of K. Again an increase was observed in treatments receiving minerals alone after 120 days corresponding decrease in water soluble and exchangeable K fractions. This variation may be due to the fixing and releasing of K according to soil environment. The fixation process of K is relatively fast at the beginning and becomes slower when approaches to the equilibrium point, whereas the release of fixed K is very slow due to the strong binding force between K and clay minerals [17, 20].
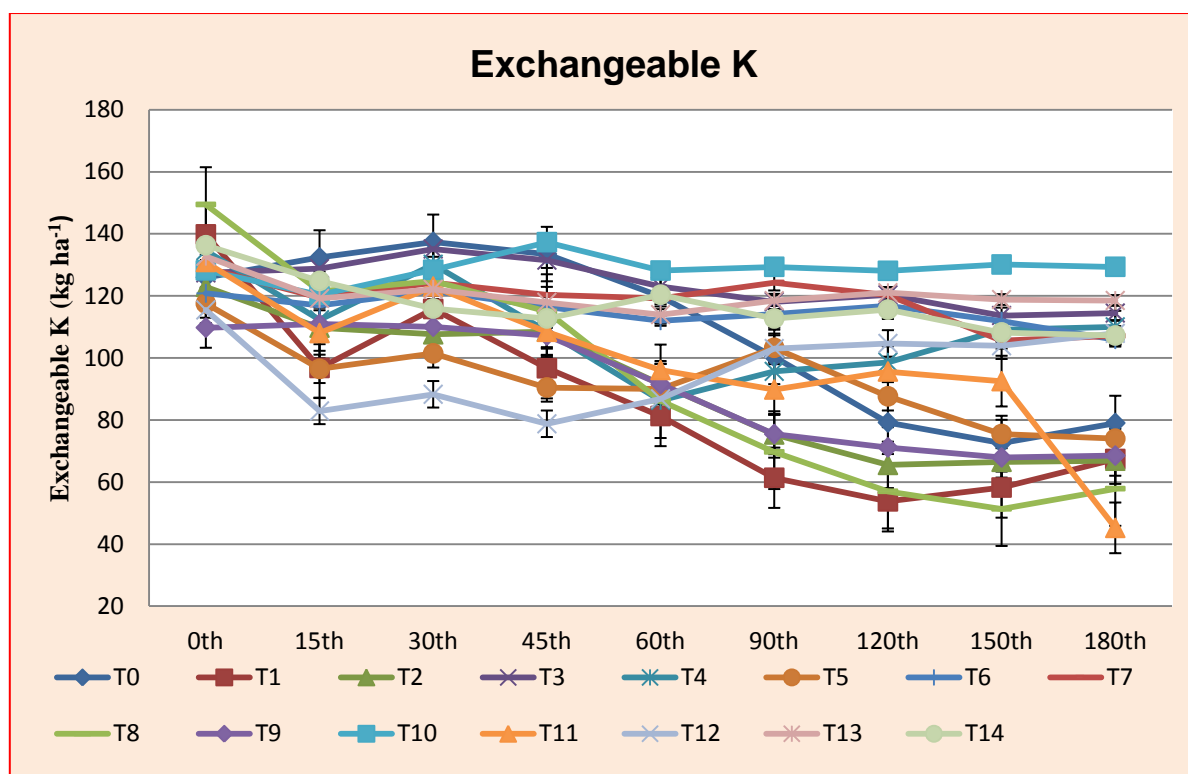
Fig. 1. Exchangeable K (kg ha^{-1}) released from mineral sources of K with and without KSB
T_0- Soil alone (Control), T_1- Sulphate of potash, T_2- Patentkali, T_3- Sylvinite, T_4- Langbeinite, T_5-Kainite, T_6- Glauconite, T_7- Rock dust, T_8- Sulphate of potash + KSB, T_9- Patentkali + KSB, T_{10}- Sylvinite + KSB, T_{11}- Langbeinite + KSB, T_{12}- Kainite + KSB, T_{13}- Glauconite + KSB, T_{14}- Rock dust + KSB

Table 1. Water soluble K (kg ha^{-1}) released from mineral sources of K with and without KSB

Treatments	Days of incubation								
	0th	15th	30th	45th	60th	90th	120th	150th	180th
T$_0$- Soil alone (Control)	26.35^{fgh}	30.90^m	35.10^l	54.05^m	67.95^l	82.90^j	101.25^k	102.00^l	100.90^j
T$_1$- Sulphate of potash	34.25^a	127.95^a	144.95^a	171.80^a	202.45^b	231.70^a	248.25^b	231.05^b	210.05^b
T$_2$- Patentkali	22.85^i	64.90^h	84.35^h	96.30^h	124.55^g	152.80^d	171.75^f	168.95^f	165.00^e
T$_3$- Sylvinite	28.65^{cde}	73.20^g	92.40^g	104.45^f	116.80^h	125.75^g	131.80^i	134.65^j	132.15^h
T$_4$- Langbeinite	29.55^{cd}	104.65^c	121.45^c	154.15^b	185.40^c	189.05^b	177.75^e	172.00^e	164.70^e
T$_5$- Kainite	27.10^{efg}	87.70^e	103.85^e	120.70^e	132.05^f	143.25^f	150.05^g	146.35^h	141.35^g
T$_6$- Glauconite	25.20^{gh}	42.85^l	54.15^k	65.25^l	80.05^k	83.10^j	85.75^m	85.15^o	86.00^l
T$_7$- Rock dust	32.90^a	51.90^j	62.00^j	72.65^k	82.35^{jk}	84.15^{ij}	89.25^l	99.15^m	90.90^k
T$_8$- SOP + KSB	32.15^{ab}	116.35^b	140.05^b	170.80^a	206.30^a	233.2^a	256.70^a	267.10^a	268.90^a
T$_9$- Patentkali + KSB	24.15^{hi}	72.25^g	84.60^h	102.30^g	131.05^g	162.10^c	183.40^d	185.55^d	191.65^d
T$_{10}$- Sylvinite + KSB	25.75^{fgh}	76.10^f	96.10^f	106.45^f	122.95^g	126.75^g	134.20^h	139.15^i	143.00^g
T$_{11}$- Langbeinite + KSB	29.80^c	106.45^c	120.90	150.15^c	173.10^d	188.10^b	193.00^c	202.00^c	205.15^c
T$_{12}$- Kainite + KSB	30.55^{bc}	90.25^d	110.30^d	135.65^d	142.05^e	147.95^e	151.90^g	158.20^g	161.60^f
T$_{13}$- Glauconite + KSB	26.00^{fgh}	47.90^k	60.15^j	75.25^j	83.05^j	85.85^i	90.15^l	94.30^n	100.25^j
T$_{14}$- Rock dust + KSB	27.50^{def}	57.85^i	68.10^i	78.75^i	92.05^i	99.95^h	104.00^j	107.85^k	114.90^i
SE (m)	0.746	0.715	0.679	0.668	0.795	0.709	0.786	0.917	0.774
CD (0.05)	2.249	2.153	2.046	2.011	2.395	2.135	2.368	2.762	2.331

Table 2. Available K (kg ha^{-1}) released from mineral sources of K with and without KSB

Treatments	Days of incubation								
	0th	15th	30th	45th	60th	90th	120th	150th	180th
T$_0$- Soil alone (Control)	152.30[h]	163.25[k]	172.50[n]	187.50[k]	187.75[n]	183.20[n]	180.45[j]	174.55[o]	177.60[k]
T$_1$- Sulphate of potash	174.05[b]	224.70[b]	260.70[b]	268.45[b]	283.70[b]	293.05[b]	302.00[b]	289.25[c]	275.20[b]
T$_2$- Patentkali	145.75[i]	174.65[h]	191.95[j]	204.75[i]	216.05[i]	228.10[i]	237.25[g]	235.45[i]	231.80[f]
T$_3$- Sylvinite	156.05[fg]	202.00[e]	227.50[e]	235.95[f]	239.80[f]	243.85[g]	252.10[f]	248.30[h]	242.55[e]
T$_4$- Langbeinite	164.10[c]	216.95[c]	251.60[c]	262.75[c]	271.70[c]	284.70[c]	276.35[d]	281.10[d]	273.45[bc]
T$_5$- Kainite	144.60[i]	184.15[g]	205.30[g]	211.15[h]	222.00[h]	246.50[g]	237.65[g]	221.80[j]	213.20[h]
T$_6$- Glauconite	146.00[i]	159.80[l]	175.70[m]	181.65[l]	192.00[m]	197.20[m]	202.55[l]	197.00[n]	189.30[j]
T$_7$- Rock dust	161.85[cd]	171.25[i]	186.20[k]	192.95[j]	201.50[k]	208.45[k]	209.45[i]	204.70[m]	195.75[i]
T$_8$- Sulphate of potash + KSB	181.60[a]	237.85[a]	264.85[a]	285.75[a]	292.45[a]	302.90[a]	313.70[a]	318.45[a]	326.55[a]
T$_9$- Patentkali + KSB	133.90[j]	183.15[g]	194.65[i]	209.50[h]	222.55[h]	237.55[h]	254.55[ef]	253.45[g]	257.65[d]
T$_{10}$- Sylvinite + KSB	153.95[gh]	196.45[f]	224.50[f]	243.75[e]	251.10[e]	256.10[e]	262.25[e]	269.25[e]	271.65[bc]
T$_{11}$- Langbeinite + KSB	160.70[de]	214.45[d]	243.90[d]	258.55[d]	269.20[d]	277.90[d]	288.60[c]	294.50[b]	200.55[i]
T$_{12}$- Kainite + KSB	146.00[i]	173.15[hi]	198.55[h]	214.40[g]	228.85[g]	250.95[l]	256.55[ef]	262.10[f]	268.95[c]
T$_{13}$- Glauconite + KSB	158.75[ef]	167.05[j]	182.25[l]	193.15[j]	197.00[l]	204.30[f]	211.15[hi]	213.10[l]	217.75[gh]
T$_{14}$- Rock dust + KSB	163.80[c]	182.65[g]	184.00[kl]	191.45[j]	212.40[j]	212.65[j]	219.55[h]	216.05[k]	221.65[g]
SE (m)	1.006	0.826	0.896	0.92	0.737	0.965	2.981	0.913	2.01
CD (0.05)	3.033	2.488	2.698	2.772	2.220	2.907	8.983	2.750	6.057

Table 3. HNO$_3$ extractable K (kg ha^{-1}) released from mineral sources of K with and without KSB

| Treatments	Days of incubation								
	0th	15th	30th	45th	60th	90th	120th	150th	180th
T$_0$- Soil alone (Control)	367.50	368.70^d	369.60^{fg}	367.85^h	366.10^i	360.80^f	358.75^f	357.40^i	357.50^j
T$_1$- Sulphate of potash	359.30	375.70^b	378.00^b	380.00^b	379.05^b	377.40^b	375.70^b	383.45^a	389.55^a
T$_2$- Patentkali	360.70	362.90^{hi}	366.75^{hi}	371.35^{ef}	370.60^{gh}	369.70^{de}	365.55^{de}	371.35^{cd}	376.60^d
T$_3$- Sylvinite	361.30	366.00^{ef}	370.10^{fg}	372.20^{de}	371.85^{ef}	369.55^{de}	367.10^{de}	375.95^b	379.85^c
T$_4$- Langbeinite	356.20	367.05^{de}	371.35^{ef}	373.45^c	372.95^{ef}	371.15^d	367.35^d	371.95^{cd}	379.80^c
T$_5$- Kainite	370.85	372.00^c	374.25^{cd}	376.20^g	377.20^{bc}	375.90^{bc}	375.10^{bc}	381.15^a	385.00^b
T$_6$- Glauconite	355.45	363.85^{fg}	365.80^{ij}	369.95^b	368.70^h	368.95^e	367.65^e	369.40^{de}	371.70^e
T$_7$- Rock dust	374.05	378.60^a	380.75^a	380.00^a	376.55^c	374.70^c	373.25^c	372.55^c	375.30^d
T$_8$- Sulphate of potash + KSB	368.90	373.75^{bc}	376.45^{bc}	382.85^{ef}	382.25^a	380.05^a	378.50^a	373.95^{bc}	368.25^f
T$_9$- Patentkali + KSB	355.20	365.15^{ef}	368.95^{gh}	372.15^c	371.20^{fg}	369.85^{de}	367.75^{de}	365.40^g	360.80^{hi}
T$_{10}$- Sylvinite + KSB	357.60	361.50^i	370.95^{fg}	376.05^{cd}	375.45^{cd}	369.70^{de}	362.80^{de}	357.65^i	355.05^k
T$_{11}$- Langbeinite + KSB	360.75	369.00^d	373.95^d	375.00^c	374.05^{de}	371.60^d	369.90^d	368.95^{ef}	361.95^{gh}
T$_{12}$- Kainite + KSB	369.20	372.40^c	373.55^{de}	376.30^c	376.20^{cd}	374.00^c	371.40^c	366.75^{fg}	364.05^g
T$_{13}$- Glauconite + KSB	362.05	363.10^{gh}	364.05^{jk}	369.60^{gh}	368.80^h	367.70^e	365.60^e	362.50^h	358.95^{ij}
T$_{14}$- Rock dust + KSB	356.50	361.85^{hi}	362.85^k	365.30^i	363.40^j	362.50^f	360.20^f	358.40^i	353.80^k
SE (m)	5.72	0.725	0.767	0.665	0.759	0.715	0.723	0.906	0.746
CD (0.05)	NS	2.184	0.896	2.004	2.288	2.154	2.178	2.730	2.257
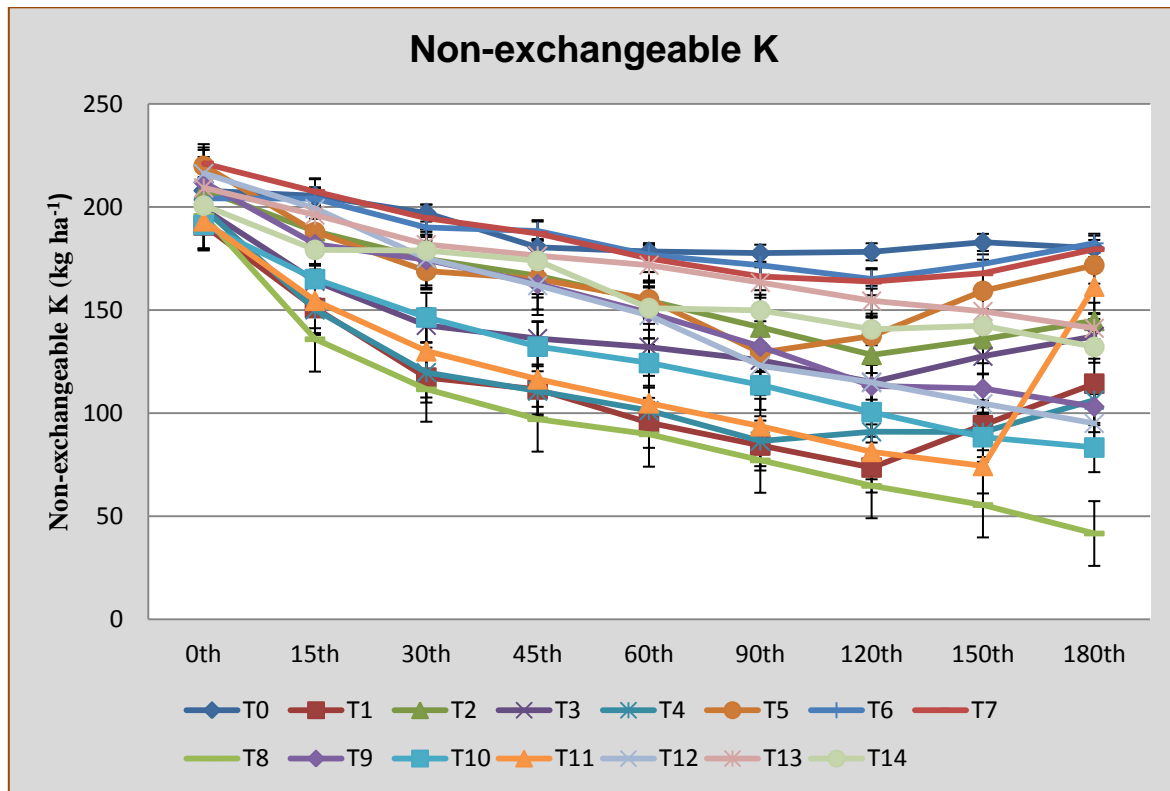
Fig. 2. Non-exchangeable K (kg ha^{-1}) released from mineral sources of K with and without KSB
T_0- Soil alone (Control), T_1- Sulphate of potash, T_2- Patentkali, T_3- Sylvinite, T_4- Langbeinite, T_5-Kainite, T_6- Glauconite, T_7- Rock dust, T_8- Sulphate of potash + KSB, T_9- Patentkali + KSB, T_{10}- Sylvinite + KSB, T_{11}- Langbeinite + KSB, T_{12}- Kainite + KSB, T_{13}- Glauconite + KSB, T_{14}- Rock dust + KSB

3.5 Non-exchangeable K

Non-exchangeable K content presented in Fig. 2 was found to be decreased gradually throughout the incubation period and increase in content was observed in the treatment receiving K minerals alone after 150th days of incubation. The higher values of non-exchangeable K content were observed on 0th day of incubation in all treatments and the highest value recorded in the treatment T_7 (rock dust, 221.10 kg ha^{-1}) followed by the treatment T_5 (kainite) which contains 219.95 kg ha^{-1} K.

The reason for the initial decline in K content may be due to the release of K from clay minerals to the soil solution. This indicates that more K$^+$ ions have tendency to release into soil solution or the fixation process occur in the soil very slowly. The red soil recorded the lowest soil fixing capacity among seven different soils while evaluating the K fixation capacity in a fifteen year long term fertilization experiment [21]. A significant portion of K (70–90%) required by the plants comes from the non-exchangeable pool in

the absence of optimum K supply in many crops [1]. The non-exchangeable K content in the treatments receiving K minerals along with KSB showed a gradual depletion throughout the incubation period. This may be due to the microbial activity which converts the unavailable form of K to the available form [10].

4. CONCLUSION

A wide variation was observed in the amount of K fraction released at different stages of incubation. Regarding the K content in various K pools, there was a gradual increase and decrease in water soluble, available and exchangeable K content during the incubation period was observed in treatment receiving K minerals alone. But the highest increase in the water soluble, available and exchangeable K was observed in treatments receiving K minerals along with KSB. The non-exchangeable K content was found to decrease gradually throughout the incubation period and slight increase in content was observed in treatments without KSB. Fluctuation of K pools at different

stages is due to the significant relationship of the different forms of K and their relative proportion in soil. By studying the release pattern of each K mineral sources through the incubation study, we could understand the rate at which each sources release K$^+$ ions into the soil. Thus we can select the best source of K which can effectively utilize for the crop cultivation. The most preferred mineral sources of K like SOP and langbeinite along with KSB can be recommended for increasing the availability of potassium in soil.

ACKNOWLEDGEMENT

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Mengel K. Dynamics and availability of major nutrients in soils. Adv. Soil. Sci. 1985;2:65–131.
2. Sardens J, Penuelas J. Potassium: a neglected nutrient in global change. Global Ecol. Biogeogr. 2015;24:261-275.
3. Xiushang Li, Tianqi Wu, Chunyan Qu, Peng Ning, Jianglan Shi, Tian X. Potassium fertilization with crop straw incorporation alters soil potassium fractions and availability in north west China: an incubation study. PloS one. 2020;15 (7).
4. Harsha BR and Jagadeesh BR. Dynamics of potassium in selected black soil type of Haveri district, Karnataka. J. of Pharmacogn. Phytochem. 2017;6(6): 2101-2106.
5. Srinivasarao C, Ali M, Ganeshamurthy A, Singh KJBCI. Potassium requirements of pulse crops. 2003;17(1):8.
6. NPOP [National Programme for Organic Production]. India Organic. Edn 6. Department of commerce, ministry of commerce and industry, New Delhi. 2005;226.
7. Suttner BV. Patentkali- delivering quality. K+S Minerals and Agriculture GmbH, Kassel; 2019. Accessed 23 march 2021.

Available:https://www.kpluss.com/en-us/our-business-products/agriculture/products/patentkali-00001/
8. Rawal N, Pande KR, Renuka S, Vista SP. Phosphorus and potassium mineralisation as affected by phosphorus levels and soil types under laboratory condition. Geosci. 2021;1-9.
9. Meena VS, Maurya BR, Verma JP, Aeron A, Kumar A, Kim K, et al. Potassium solubilizing rhizobacteria (KSR): isolation, identification, and K-release dynamics from waste mica. 2015;81:340-347.
10. Swamanna J, Kavitha P, Sreenivasa chari M, Srinivasa reddy M. Potassium dynamics in relation with soil properties in rice growing soils of Kurnool district, Andhra Pradesh. Andhra Pradesh J Agril. Sci. 2015;1(3):15-20.
11. Jackson ML. Soil Chemical Analysis, Prentice Hall of India Private Limited, New Delhi; 1973.
12. Wood LH, De Turk EE. The adsorption of potassium in soils in non-exchangeable forms. Proc. Soil Svi. Soc. Am. 1941;19: 98-99.
13. Srinivasrao C, Srinivas K. Potassium Dynamics and Role of Non-exchangeable Potassium in Crop Nutrition. Indian J. of Ferti. 2017; 13 (4):80-94.
14. Sparks DL. Bioavailability of soil potassium. Handbook of Soil Science (M.E. Sumner, Ed.). CRC Press, Boca Raton, USA, 2000, 38- 52.
15. Friedrich S, Platonova NP, Karavaiko GI, Stichel E, Glombitza F. Chemical and microbiological solubilization of silicates. Acta Biotechnol. 2004;11:187–196.
16. Jessymol AS, Mariam KA. Transformation of added potassium in laterite soils. J. Trop. Agric. 1993; 31: 29-33.
17. Wakeel A, Gul M, Sanaullah M. Potassium dynamics in three alluvial soils differing in clay contents. Emirates J. Food and Agric. 2013;25:39-44.
18. Das K, Sarkar D, Nayak DC. Forms of potassium and their distribution in some soils representing red and lateritic ecosystem of West Bengal. J. Pot. Res. 2000;16:1-6.
19. Oborn I, Andrist-Rangel Y, Askekaard M, Grant CA, Watson CA, Edwards AC. Critical aspects of potassium management in agricultural systems. Soil Use Manage. 2005;21:102–120.

20. Zhang H, Xu M, Zhang W. Factors affecting potassium fixation in seven soils under 15-year long-term fertilization. Chin. Sci. Bull. 2009;54:1773–1780.

21. Karimi E, Abdolzadeh A, Sadeghipour HR, Aminei A. The potontial of glauconitic sandstone as a potassium fertilizer for olive plants. Arch. Agron. Soil Sci. 2011;1: 1-11.

Peer-review history:
The peer review history for this paper can be accessed here:
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