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Potassium Solubilizer Induced Dynamics of Potassium in Varied Mineralogy and Available K Soils of Eastern Dry Zone of Karnataka, India

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Abstract

Background: Potassium being a major nutrient in plant nutrition plays important role in activation of more than 60 enzymes in plants. Its availability is major constrain in different soils which mainly depends on minerology of the soil and form in which it is present *Viz*., Water-soluble (readily available), Exchangeable (readily available) and non-exchangeable (slowly available) these are very much available forms of potassium and the lattice/mineral form is very slowly available form of nutrient. Wherein, mineral has to weather and need to add to the soil available form but there exists the dynamic equilibrium between all these 4 forms of potassium. On other hand, potassium solubilizers has an ability to solubilizes the mineral K which helps in boosting potassium availability by converting insoluble mineral K to soluble K by releasing organic acids.

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Aim: To study the existence of dynamic equilibrium existing between the different forms of potassium with K- solubilizer and fertilizer application in different minerology and available K status of soils**.**

Study Design: Completely randomised design with four treatment and 3 replications.

Place and Duration: A pot culture experiment was conducted in green house at university of agricultural sciences, Bengaluru, Karnataka, India and soil were incubated for 15, 30, 60 and 120 days.

Methodology: The study consists of 3 different soils with low, medium and high in available potassium content collected form Eastern dry zone of Karnataka. The samples were subjected to X-ray diffraction (XRD). Later, 4 treatments were induced *Viz.*, control, Fertilizer-K, K-solubilizer and K-fertilizers + K solubilizers for each soil. The treatments were replicated thrice for each treatment and soils were kept for incubation studies by maintain moisture at field capacity and destructive soil sampling was done at 15, 30, 60 and 120 Days after incubation and were analysed for potassium fractions.

Results: Application of K solubilizer to low, medium and high available K soils mainly in K-solubilizer treatment and fertilizer-K + K-solubilizers has led to release of non-exchangeable K into water-soluble and exchangeable with 37, 30 and 11.61 % increase in water soluble K over the initial value in low, medium and high K soils respectively in K-solubilizer treatment and 132 , 53.46 and 46.07 increase in water soluble K in low, medium and high K soils respectively, over the initial values in the Fertilizer K + K-solubilizer treatment. Exchangeable K was increased upto 7.05, 6.96 and 3.22 % over the initial K in K-solubilizer treatments in low, medium and high K soils respectively in K- solubilizer treatment and 15.22, 14.99 and 8.32 % increase in exchangeable K was recorded in Fertilizer-K + K-solubilizer treatment in low, medium and high K soils respectively. Both this forms water soluble and exchangeable are mainly bio available for the plant. On other hand there was concomitant decrease in non-exchangeable K with increase in water soluble and exchangeable K in the said treatments.

Conclusion: application of K-solubilizers helps in brining non-exchangeable form of potassium into water soluble and exchangeable form thereby decreases the fixation of K in different mineralogy soils.

Keywords: Potassium solubilizer; mineralogy; soil; plant nutrition; K Soils.

1. Introduction

The concentration of plant-available potassium (K) in soils is largely governed by the degree of weathering and the nature of the parent material, both of which exert a direct influence on its supply. Potassium in soils occurs in four principal forms: structural (lattice or mineral) K, exchangeable (readily available) K, non-exchangeable or fixed (slowly available) K, and water-soluble (readily available solution) K (Rehm and Schmitt, 2002). It has been estimated that more than 90% of total soil K is contained within primary minerals (lattice/mineral forms), whereas only approximately 0.2% is present in the soil solution as immediately plant-available K, despite this fraction constituting the primary source for plant uptake.

Water-soluble K represents the fraction directly accessible for plant and microbial uptake and is also the most susceptible to leaching losses. Its concentration in the soil solution is generally low unless recent potassium fertilisation or amendment has occurred. Moreover, the level of solution K is regulated by dynamic equilibrium and kinetic exchanges among different soil K pools, soil moisture status, and the concentrations of divalent cations present in both the soil solution and exchange complex (Sparks and Huang, 1985). Exchangeable K refers to the fraction electrostatically adsorbed as an outer-sphere complex on the surfaces of clay minerals and organic matter, particularly humic substances. This form is readily exchangeable with other cations and serves as an important and immediately available reservoir for plant nutrition. The concentration of K in the soil solution is strongly influenced by plant uptake, which continuously depletes solution K and is replenished through the release of K from exchange sites on clay minerals. However, this fraction is also vulnerable to leaching losses under conditions of high rainfall or irrigation (Haby et al., 1990).

Non-exchangeable K is only moderately to sparingly available to plants, as it is released slowly over time through weathering and structural breakdown of minerals. Higher concentrations of non-exchangeable K are generally observed in sub-surface soils compared with surface horizons. Soils rich in illitic clay minerals tend to contain greater amounts of non-exchangeable K in sub-surface layers due to their strong K-fixing capacity associated with fine clay and silt fractions (Sharma et al., 2009). The extent of K fixation is influenced by the quantity of K released from clay minerals, particle size distribution, and the type and abundance of clay minerals, all of which are closely linked to soil texture. Consequently, both the amount of K fixed in soils and the mineralogical composition significantly affect the subsequent release of K to plants (Rao et al., 2001).

Potassium solubilizing microorganisms (KSM) solubilize mineral potassium that are unavailable to plant to become accessible and available to plant (Meena et al. 2016), KSM mobilizes K from soil mineral making such available to plants (Pandey et al. 2020). There are certain soil microorganisms which are able to solubilize unavailable form of K from the K-bearing minerals *viz.,* micas, illite, orthoclase's etc. The solubilization could be attributed to organic acids which either directly dissolves rock K or chelate silicon ions to bring K into solution (Groudev, 1987; Friedrich et al*.,* 1991; Ullman, et al., 1996 and Bennet et al., 1998).

Potassium-solubilising bacteria (KSB) are generally present in most soils; however, their abundance, diversity, and K-solubilisation efficiency vary considerably depending on soil characteristics and prevailing climatic conditions. These microorganisms are capable of dissolving silicate minerals and mobilising potassium through several biochemical mechanisms, including the production of organic and inorganic acids, acidolysis, polysaccharide secretion, complexolysis, chelation, and ion-exchange reactions. Consequently, the application of K-solubilising bacteria represents a promising strategy for enhancing potassium availability, particularly in crops with high K demand (Zahar et al., 1984; Vandevivaea et al., 1994; Barker et al., 1998). Jain et al. (2022) further emphasised that potassium-solubilising microorganisms (KSMs) are able to transform insoluble mineral potassium into plant-available forms, thereby improving soil potassium availability. This highlights their potential role in potassium nutrient management, especially under K-limited soil conditions, and their capacity to reduce reliance on chemical potassium fertilisers. This functional importance is attributed to the active involvement of soil microorganisms, including KSMs, in the natural potassium cycling processes within the soil ecosystem (Hamid and Bashir, 2019).

2. Materials and Methods

2.1 X- Ray Diffraction Analysis

Mineral composition of three soil samples of low, medium and high available K from the Eastern dry zone of Karnataka was determined by X-ray diffraction for powdered soil sample and by separating the clay fractions using a Philips MPD 3710 (Cobalt anti–cathode) X-ray diffractometer following procedure as outlined by Shrivastava (2009). The soil samples were ground to fine powder and mineralogical properties were studied by two methods: 1) Powder diffraction for bulk soil samples 2) Separation of clay fractions for identifying the secondary clay minerals.

2.2 Incubation Studies Setup

Three soil samples were collected from eastern dry zone of Karnataka, covering low, medium and high in available potassium content. The initial physico-chemical properties of soil and geo coordinates are given in (Table 1).

All the three soils were weighed and transferred to pot (200 gm per pot), 20 ppm (40 kg /ha) of fertilizer K (MOP) and 10 ml of K-solubilizer (*Frateuria aurantia*) containing 10^8 colony forming units per ml was applied as per the treatments. The moisture content was maintained at field capacity in low available K (17 %) medium available K (30 %) and high available K soils (26 %) and loss of moisture was maintained daily by weighing each pot till 120 days. Destructive sampling of soil was carried out at 15, 30, 60 and 120th day after incubation (DAI) by mixing soil in each pot and the samples were periodically analysed for different forms of potassium.

2.3 Treatment Imposition

Total 4 treatments were imposed for each soils T_1: Control T_2: Fertilizer K (20 ppm of K) T_3: Fertilizer K + K solubilizer (20 ppm of K and 10 ml of 10^8 colony forming units per ml of *Frateuria aurantia* and T_4: K-solubilizer (10 ml of 10^8 colony forming units per ml of *Frateuria aurantia*) these treatments were replicated thrice in each soil (Low, Medium and High available K).

2.4 Soil Analysis

Destructive soil samples collected at 15, 30, 60 and 120 days after incubation were analysed form different forms of potassium Viz., water soluble-K, Exchangeable-K and Non -Exchangeable K.

Water-soluble potassium was determined in 1:2 soil water suspensions after shaking for two hours and allowing the suspension to stand for an additional 16 hours (Mac Lean, 1961). The potassium in the extract was determined by flame photometer.

Table 1. Initial physico-chemical properties of the soils from Eastern dry zone of Karnataka

Soil parameters	Low	Medium	High	Methods
Latitude and Longitude of sample collected	13° 24’ 27.5’’ N 77° 23’ 11.3’’ E	13° 29’ 10.2’’ N 77° 18’ 47.0’’ E	13° 27’ 20.4’’ N 77° 23’ 55.1’’ E	GPS GPS
Particle size distribution (%)				
Sand (%)	74.40	62.97	65.12	International Pipette method
Silt (%)	7.60	8.53	10.23	
Clay (%)	18.00	28.50	24.65	
Soil texture	Sandy loam	Sandy clay loam	Sandy clay loam	
Bulk density (g cm^{-3})	1.59	1.42	1.46	Piper, 1966
Field capacity (%)	17	30	26	Pressure plate apparatus
pH (1: 2.5)	5.26	5.84	6.02	Jackson, 1973
EC (dS m^{-1})	0.161	0.295	0.118	Jackson, 1973
OC (%)	0.46	0.63	1.02	Jackson, 1973
CEC (cmol (p^{+}) kg^{-1})	8.6	13.2	17.6	Jackson, 1958
Available K_2O (kg ha^{-1})	97.2	171.6	342.6	Jackson, 1973
Water soluble K (mg kg^{-1})	5.20	10.60	17.80	Mac Lean, 1961
Exchangeable K (mg kg^{-1})	38.55	58.15	98.45	Knudsen et al. (1982)
Non exchangeable K (mg kg^{-1})	236.25	259.25	295.75	Knudsen et al. (1982)
Lattice K (mg kg^{-1})	1970	3047	2338	By subtracting all the fractions from the total K
Total K (mg kg^{-1})	2250	3375	2750	Lim and Jackson, 1982

Exchangeable potassium was determined using neutral normal ammonium acetate (NH_4OAc) extraction following the procedure described by Knudsen et al. (1982). Ten grams of soil were shaken with 25 mL of neutral N NH_4OAc solution for 10 minutes and subsequently centrifuged. The supernatant was carefully decanted into a 100 mL volumetric flask. This extraction procedure was repeated three additional times, and the combined extracts were made up to volume with NH_4OAc solution. Potassium concentration in the extract was then quantified using a flame photometer. Exchangeable potassium was calculated by subtracting water-soluble potassium from NH_4OAc-extractable potassium.

Non-exchangeable potassium was determined using the boiling 1 N HNO_3 method as outlined by Knudsen et al. (1982). A 2.5 g sample of finely ground soil was gently boiled with 25 mL of 1 N HNO_3 for 10 minutes and subsequently cooled. The mixture was filtered, and the filtrate was collected in a 100 mL volumetric flask. The residue was then washed four times with 15 mL of 0.1 N HNO_3. After making up the volume and thorough mixing, potassium concentration in the extract was determined using a flame photometer. Non-exchangeable potassium content was estimated by subtracting NH_4OAc-extractable potassium from the total potassium obtained through the acid extraction.

2.5 Statistical Data Analysis

The statistical analysis was carried out by WASP - Web Agri Stat Package 2.0 software at 1% significant level and per cent increase or decrease over the initial value at different day of incubation (15, 30, 60 and 120 DAI) by comparing the different fraction data with the initial data.

3. Results and Discussion

3.1 Results

3.1.1 X-ray Diffraction

Results of XRD analysis of low, medium and high available K soils (Table 2 and Figs. 1, 2 and 3) indicates that quartz, feldspar and muscovite were present in coarse fraction of soils as major primary minerals. Whereas, muscovite was present only in low available K soils.

Table 2. XRD-analysis of low, medium and high available K soils from Eastern dry zone of Karnataka

	Category	Primary minerals	Secondary minerals
1	Low available K	Quartz, Feldspar, Muscovite	Kaolinite/Vermiculite
2	Medium available K	Quartz, Feldspar	Illite, Vermiculite and Kaolinite
3	High available K	Quartz, Feldspar	Illite and Kaolinite

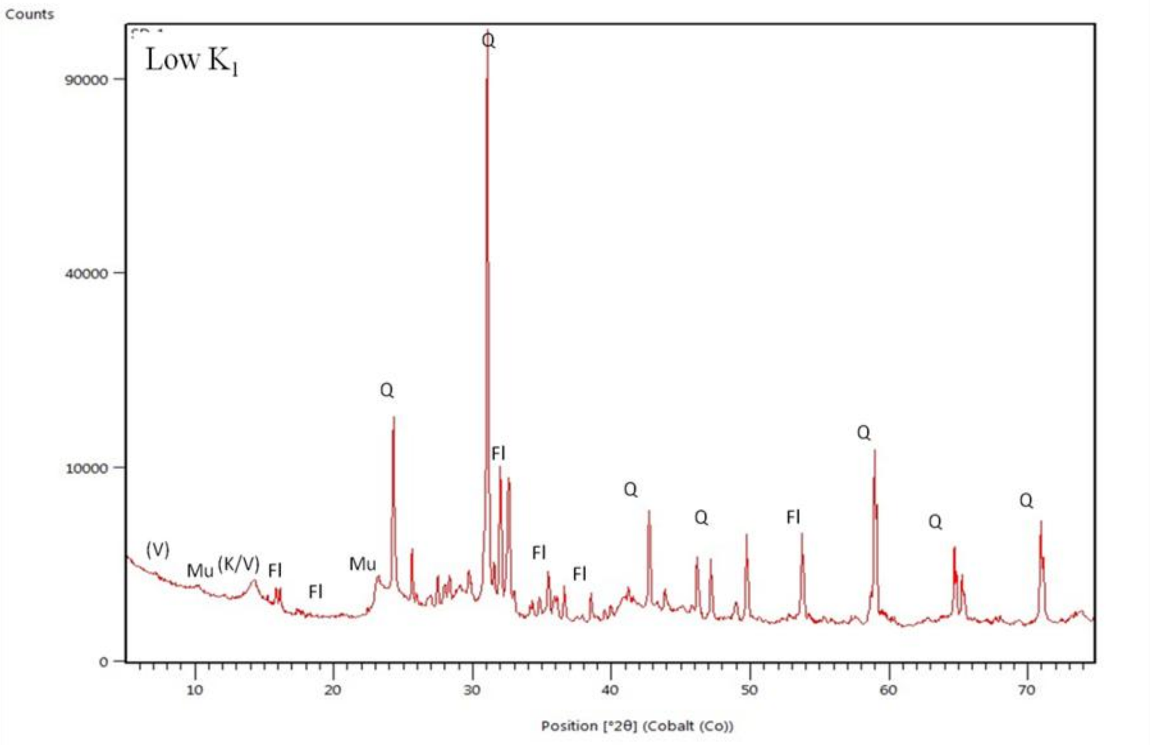

Fig. 1. XRD-Diffractogram of low availabe K soil in Eastern dry zone of Karnataka (Q- Quartz; Fl – Feldspar; Mu – Muscovite; K – Kaolinite; V – Vermiculite; () – Low quantity; -dominant)

Among the secondary clay minerals kaolinite, vermiculite and illite are dominant. Illite was dominant in medium available K and high available K soils and kaolinite was present in all three soils.

3.1.2 Water-Soluble K

There was a significantly higher water-soluble K release among the different treatments in low available K soils at different days of incubation (Table 3). The significantly higher values of 13.83, 14.57, 12.40, 12.17 mg kg^{-1} of water-soluble K was recorded in treatment receiving Fertilizer- K + K- solubilizer over the other treatments at 15, 30, 60 and 120 DAI, respectively. However, the higher water-soluble K was recorded (14.33 mg kg^{-1}) at 30 DAI in Fert. K + K solubilizer treatment which increased to an extent of 175.64 per cent over the initial value (5.6 mg kg^{-1}).

Table 3. Dynamics of potassium in low available potassium containing soils at different days after incubation

Treatments	**Water soluble- K (mg kg^{-1})**				**Exchangeable- K (mg kg^{-1})**				**Non-exchangeable- K (mg kg^{-1})**			
	Days After Incubation (DAI)				**Days After Incubation (DAI)**				**Days After Incubation (DAI)**			
	15	**30**	**60**	**120**	**15**	**30**	**60**	**120**	**15**	**30**	**60**	**120**
T$_1$: Control	5.27c (1.28)	5.13d (-1.28)	4.80d (-7.69)	4.60d (-11.54)	38.98c (1.12)	37.28b (-3.29)	36.62c (-5.02)	36.23c (-6.01)	235.75 (-0.21)	237.58 (0.56)	238.58 (0.99)	239.17 (1.23)
T$_2$: Fertilizer-K	12.40b (138.46)	11.27b (116.67)	10.50b (101.92)	10.40 b (100.00)	43.27^{ab} (12.24)	41.90a (8.69)	41.00 b (6.36)	39.35b (-2.08)	239.33 (1.31)	242.67 (2.72)	243.5 (3.07)	245.25 (3.81)
T$_3$: K- solubilizer	6.20c (19.23)	7.73c (48.72)	7.13c (37.18)	7.00c (34.42)	39.72bc (3.03)	41.27a (7.05)	40.78b (5.79)	39.00b (1.17)	235.42 (-0.35)	233.33 (-1.23)	234.75 (-0.63)	238.00 (0.74)
T$_4$: Fert. K + K- solubilizer	13.80a (165.38)	14.33a (175.64)	12.07a (132.05)	11.87a (128.62)	43.78a (13.58)	44.42a (15.22)	43.27a (12.24)	42.13a (9.30)	240.08 (1.62)	240.80 (1.92)	241.70 (2.30)	241.83 (2.36)
CD@1%	1.76	3.27	2.05	1.58	NS	4.78	3.09	3.49	NS	NS	NS	NS
Initial	5.20				38.55				236.25			

❖ *Figures in parenthesis indicate per cent increase over initial value*

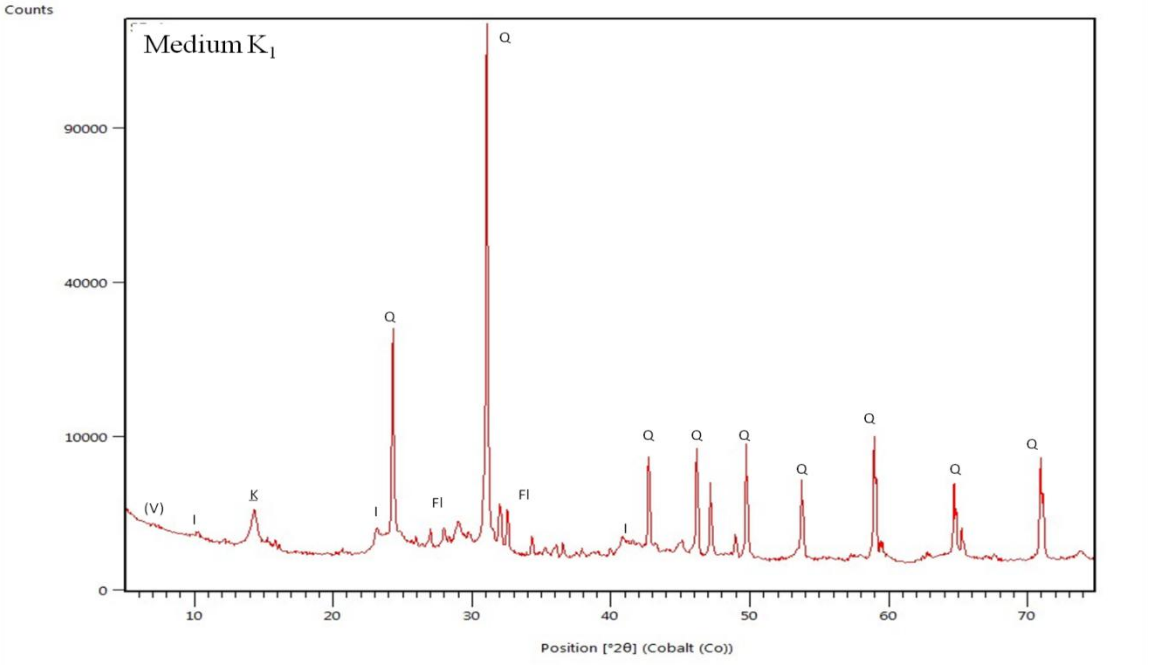

Fig. 2. XRD-Diffractogram of medium available K soils in Eastern dry zone of Karnataka (Q- Quartz; Fl – Feldspar; Mu – Muscovite; K – Kaolinite; V – Vermiculite; I – Illite; () – Low quantity; dominent)

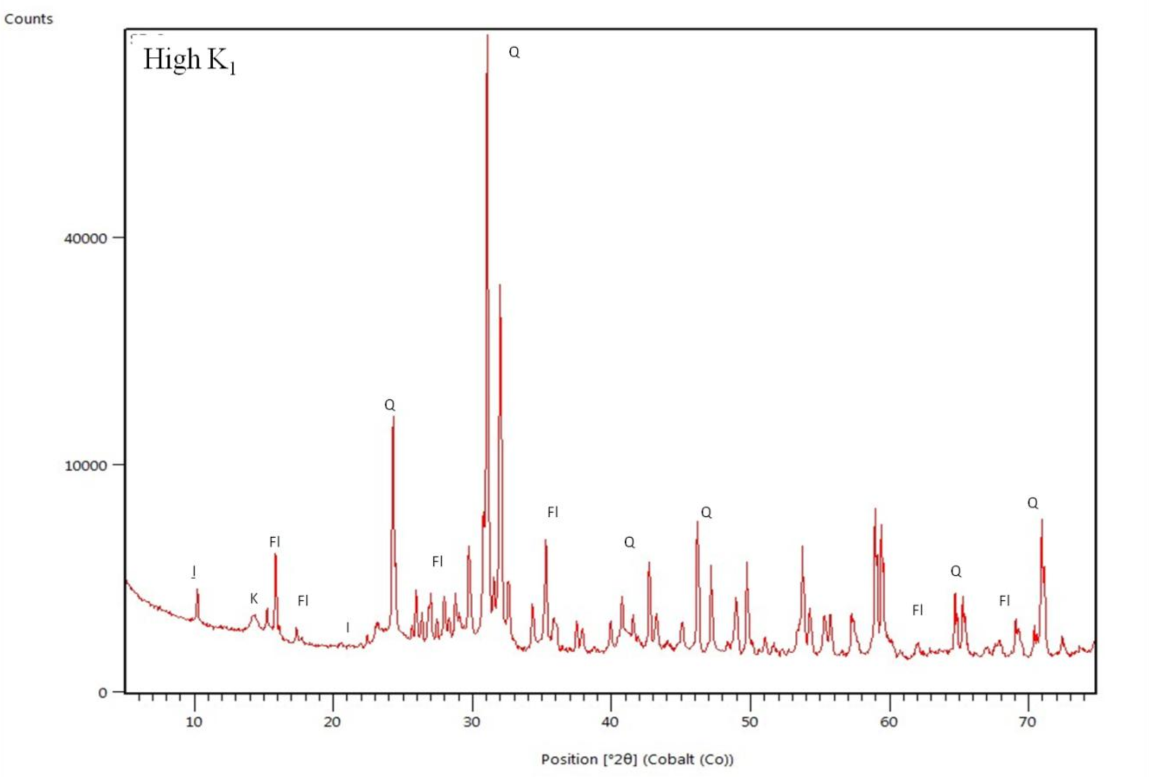

Fig. 3. XRD-Diffractogram of high available K soils in Eastern dry zone of Karnataka (Q- Quartz; Fl – Feldspar; Mu – Muscovite; K – Kaolinite; V – Vermiculite; I – Illite; () – Low quantity; dominent)

There was significant difference in water-soluble K among the treatments in medium available K soils (Table 4). Significantly higher water-soluble K (18.07, 19.47, 16.27 and 15.67 mg kg^{-1}) was recorded in treatment receiving Fertilizer- K + K-solubilizer over other treatments at 15, 30, 60 and 120 DAI, respectively. The perusal of data clearly indicated that water soluble K increased up to 30 days of incubation in all the treatments except control. But, later it decreased up to 120 DAI.

Significantly higher water-soluble K (25.73, 27.20, 26.00 and 25.20 mg kg^{-1}) was recorded in treatment receiving Fert. K + K solubilizer (Table 5) compared to other treatments at 15, 30, 60 and 120 DAI, respectively. However, there was decrease in water soluble K at 60 DAI (17.40 mg kg^{-1}) and 120 DAI (16.87 mg kg^{-1}) over the initial content (17.3 mg kg^{-1}) in treatment which did not receive Fert. K or K solubilizer (control).

Irrespective of the soils, water-soluble K release over the days (15, 30, 60 and 120 DAI) was found to be more in Fert. K + K- solubilizer > Fertilizer-K > K- solubilizer > Control treatments.

3.1.3 Exchangeable-K

There was significant difference in exchangeable K among the different treatments at all stages of incubation in low available K soil (Table 3). Significantly higher values (43.78, 44.42, 43.27 and 42.13 mg kg^{-1}) of exchangeable K were recorded in treatment receiving Fert. K + K solubilizer compared to other treatments at 15, 30, 60 and 120 DAI, respectively. However, decrease in exchangeable K (38.98, 37.28, 36.62 and 36.23 mg kg^{-1}) over initial value (38.55 mg kg^{-1}) was recorded in control treatment which did not receive Fert. K or K solubilizer at 30, 60, 90 and 120 DAI, respectively.

In medium available K soil (Table 4), significantly higher value (65.18, 66.87, 65.07 and 62.00 mg kg^{-1}) of exchangeable K was recorded in Fert. K + K solubilizer treatment over the other treatments at 15, 30, 60 and 120 DAI, respectively, except Fert. K treatment which was statistically on par at 15 (63.32 mg kg^{-1}) and there was decreasing trend in exchangeable- K in control treatment at 30, 60 and 120 DAI (57.92, 56.47 and 55.42, respectively) over the initial value.

In high available K soils significant difference in exchangeable K was noticed between different treatments at all stages of incubation (Table 5). Significantly higher amount (104.10, 106.63 and 103.88 mg kg^{-1}) of exchangeable K was released compared to all other treatments in Fert. K + K solubilizer treatment at 15, 30, 60 and 120 DAI, respectively. Moreover, per cent increase in exchangeable K over initial content also recorded higher in the same treatment at all stages of incubation. But, per cent increase compared to the initial content was negative in control which did not receive Fert. K or K solubilizer.

Overall, irrespective of the soils taken in present studies, exchangeable K release over the days (15, 30, 60 and 120 DAI) was found to be more in Fert. K + K- solubilizer> Fertilizer-K> K- solubilizer > Control treatments.

3.1.4 Non-exchangeable K

Irrespective of three different soils (low, medium and high available K) studied in the present experiment there was no significant difference in non-exchangeable K content in soil at 15, 30, 60 and 120 DAI in different treatments. However, there was decrease in non-exchangeable K was recorded in K- solubilizer treatments (T_3 and T_4) all the three soil in the present studies.

3.2 Discussion

3.2.1 X-ray Diffraction

The presence of feldspar and muscovite were present in coarse fraction of soils as major primary minerals in three soils studied. Whereas, presence of muscovite only in low available K soils. As a rule, the dioctahedral micas such as muscovite are more resistant to weathering than trioctahedral micas such as biotite and phlogophite. Consequently, muscovite is more likely to occur in weathered soils compared to that of biotite or phlogophite among the mica group (Schulze, 1989).

Table 4. Dynamics of potassium in medium available potassium containing soils at different days after incubation

Treatments	Water soluble- K (mg kg^{-1})				Exchangeable- K (mg kg^{-1})				Non-exchangeable- K (mg kg^{-1})			
	Days After Incubation (DAI)				Days After Incubation (DAI)				Days After Incubation (DAI)			
	15	30	60	120	15	30	60	120	15	30	60	120
T_1: Control	10.80d	10.67d	10.53c	10.00c	58.87c	57.92	56.47b	55.42b	258.33	259.42	261.00	262.58
	(1.89)	(0.63)	(-0.63)	(-5.66)	(1.23)	(-0.45)	(-2.89)	(-4.70)	(-0.35)	(0.06)	(0.68)	(1.29)
T_2: Fertilizer-K	14.6b	15.87b	15.63a	14.40a	63.32ab	61.38	60.23b	60.17a	264.42	265.58	266.47	267.60
	(37.74)	(49.69)	(47.48)	(35.85)	(8.89)	(5.56)	(3.58)	(3.47)	(1.99)	(2.44)	(2.78)	(3.22)
T_3: K- solubilizer	11.87c	14.47c	13.80b	12.20b	61.80b	62.20	59.45b	59.38a	254.25	252.67	257.75	263.42
	(11.95)	(36.48)	(30.19)	(15.09)	(6.42)	(6.96)	(2.24)	(2.12)	(-1.93)	(-2.54)	(-0.58)	(1.61)
T_4: Fert. K + K- solubilizer	18.07a	19.47a	16.27a	15.67a	65.18a	66.87	65.0a	62.00a	260.08	258.83	264.67	265.17
	(70.44)	(83.65)	(53.46)	(47.80)	(12.10)	(14.99)	(11.89)	(6.62)	(0.32)	(-0.16)	(2.09)	(2.20)
CD@1%	1.51	1.58	2.16	2.56	3.75	NS	3.46	4.61	NS	NS	NS	NS
Initial	10.60				58.15				259.25			

❖ *Figures in parenthesis indicate per cent increase over initial value*

Table 5. Dynamics of potassium in high available potassium containing soils at different days after incubation

Treatments	Water soluble- K (mg kg^{-1})				Exchangeable- K (mg kg^{-1})				Non-exchangeable- K (mg kg^{-1})			
	Days After Incubation (DAI)				Days After Incubation (DAI)				Days After Incubation (DAI)			
	15	30	60	120	15	30	60	120	15	30	60	120
T_1: Control	18.13c	17.93	17.40	16.87	100.2	97.98c	97.27	97.05b	293.67	295.42	297.00	298.08
	(1.87)	(0.75)	(-2.25)	(-5.54)	(1.78)	(-0.47)	(-1.20)	(-1.42)	(-0.70)	(-0.11)	(-0.42)	(0.79)
T_2: Fertilizer-K	23.47b	23.60b	22.93b	22.70b	101.20b	100.75b	99.73b	99.67b	302.67	301.98	303.67	304.47
	(31.84)	(32.58)	(28.84)	(27.53)	(2.79)	(2.34)	(1.30)	(1.24)	(2.34)	(2.11)	(2.68)	(2.95)
T_3: K- solubilizer	20.00c	21.47c	19.87c	19.87c	100.75c	101.62b	99.30b	98.22b	291.58	290.25	294.33	296.42
	(12.36)	(20.60)	(11.61)	(11.61)	(2.34)	(3.22)	(0.86)	(-0.24)	(-1.41)	(-1.86)	(-0.48)	(-0.23)
T_4: Fert. K + K- solubilizer	25.73a	27.20 a	26.00a	25.20a	104.10a	106.63a	104.67a	103.88a	298.00	295.83	298.33	302.92
	(44.57)	(52.81)	(46.07)	(41.57)	(5.74)	(8.31)	(6.31)	(5.52)	(0.76)	(-0.03)	(0.87)	(2.39)
CD@1%	3.20	2.07	2.72	1.24	1.24	3.11	5.24	4.02	NS	NS	NS	NS
Initial	17.80				98.45				295.75			

❖ *Figures in parenthesis indicate per cent increase over initial value*

Among the secondary clay minerals kaolinite, vermiculite and illite are dominant. Illite was dominant in medium available K and high available K soil and kaolinite was present in all the soils. The kaolinite was observed in low available K soil, may be the reason for low available K in these soils. This might be due to low surface areas and low CEC mainly in Kaolinite dominated clays (Dixon, 1989). There is an inverse relation between soil fertility and kaolinite content because kaolinite has neither cation exchange capacity nor cations which can be attracted and desorbed by plants. Further it is devoid of potassium, and hence not a reservoir of this element. Thus, kaolinite is often more of hindrance to agricultural productivity of soil than anything else (Velde and Meunier, 2008).

Presence of vermiculite and illite in medium and high available K soils, except high available K which is devoid of vermiculite, may be the reason for these soils to be categorized under medium and high available K soils. Wherein, vermiculite has a layer charge of 0.9 to 0.6 and contains exchangeable cations, primarily Ca and Mg in the interlayer. The high charge per formula unit gives vermiculite a high CEC and causes them to have a highly affinity for weakly hydrated cations such as K^+, NH_4^+, and Cs^+. Fixation of K^+ by vermiculites can be significant in soils high in vermiculite. On the other hand, presence of illite, non-expandable secondary clay mineral with 0.8 to 0.6 inter layer charge and ionic substitution occurring in both tetrahedral and octahedral sites of mica structure enable more cations preferably hydrated K^+ ion occupy space and makes them rich in potassium content.

3.2.2 Water-soluble K

In the present investigation, an increase in water-soluble potassium was observed up to 30 days after incubation (DAI) in soils with low, medium, and high levels of available K. This trend may be attributed to the release of potassium from non-exchangeable pools, as water-soluble and exchangeable fractions constitute the readily available forms of K. A dynamic equilibrium exists among the different soil potassium pools, whereby a depletion in one fraction is compensated by replenishment from another. However, the gradual decline in water-soluble K observed at 60 and 120 DAI may be explained by a shift in equilibrium from the solution phase towards non-exchangeable forms. This process is likely driven by increased K concentration in the soil solution, after which potassium progressively migrates into fixed sites within clay minerals, thereby reducing its soluble fraction in the soil solution (Swamanna, 2015).

The percentage increase in water-soluble K over the initial content was higher in low and medium available K soils compared with high K soils. This response may be attributed to the predominance of kaolinitic clay minerals in these soils, which exhibit lower K-fixation capacity due to reduced surface charge density. Consequently, a greater proportion of added potassium remained in the soil solution in low and medium K soils. Similar observations were reported by Srinivasa Rao et al. (2000), who noted that soils dominated by illitic clays exhibit higher K fixation, followed by smectitic and kaolinitic soils, with these differences being primarily associated with variations in soil texture and mineralogical composition.

The significantly higher water-soluble K in Fert. K + K solubilizer applied treatment in the present study might be due to potassium solubilizing microorganism (*Frateuria aurantia*) which solubilized the unavailable forms of K in K bearing minerals such as mica, illite and orthoclase through production and excretion of organic acids like citric, oxalic and tartaric acids (Subhashini, 2015). These organic acids produced by microbes facilitate the weathering of minerals by dissolving K from the rocks or through formation of metal-organic complexes by forming chelate with silicon ions and bring the K into solution. Similar findings were reported by Basak and Biswas (2009), who reported that treatment receiving mica along with bacterial strain *Bacillus mucilaginosus* enhanced water-soluble K.

The per cent increase in water soluble-K due to K solubilizer was more in low-K soils compared to high available K soils at all stages of incubation, which is mainly due to release of non-exchangeable K or fixed K into solution by acids released by K solubilizer, later fixation of released K will be less in low available K soils compared to high available K soils, which is mainly due to dominance of kaolinite group clay minerals which has low CEC compared to high available K soils dominated by illite group of clay minerals. The results are in accordance with Bandopadhyay and Goswamy (1988), who noticed largest decrease in K fixation capacity of laterite soil at higher levels of K applied as compared to alluvial soil, and it was attributed to dominance of kaolinite clay mineral and lowest clay content in laterite soil which showed low K fixation capacity.

The percent increase in water soluble K with different treatments varied between among the three different soils in the present studies, might be due to variation in the clay content, CEC and amount and type of clay minerals in these soils, which directly influences the forms of K in soil. The results of the present study are in corroboration with Talele et al. (1993), who found varied amount water soluble K in incubation studies conducted to know the transformation of available K and non-exchangeable K in different soils of Maharashtra, due to variation in pH, clay content and CEC.

3.2.3 Exchangeable-K

In the present study, there was an increase in exchangeable K up to 15 DAI in low and medium available K soils, and upto 30 DAI in case of high available K soils. Moreover, lesser K fixation was recorded at later stages of incubation in low and medium available K soils compared to high available K soils. This might be due to difference in clay content, organic carbon and mineralogy, where higher clay content might have released large portion of non-exchangeable K in initial days. But, at later days of incubation it might have fixed more K. Present findings corroborate with the findings of Sanjeev, (2014) who observed that soils with higher non-exchangeable K released under K stress and also fixed higher K when supplied with K at harvest of wheat–maize cropping sequence.

Significantly higher exchangeable K in Fert-K+ K-solubilizer treatment compared to the other treatments, might be due lesser fixing of added K and higher solubilization of non-exchangeable pool to the exchangeable pool due to release of organic acids by *Frateuria aurantia.* Similar findings were made by Badr (2006) who found that potassium from feldspar mineral was solubilized and transformed into available form as evident from higher available K in silicate dissolving bacteria was inoculated.

Per cent increase compared to the initial exchangeable K in Fert. K treatment was higher in low and medium available K soils compared to high available K soils even though clay content was higher in high available K soils compared to low and medium available K soils containing low clay. This might be due to saturation of exchange sites of K due to continuous use of K fertilizers over long period. Similarly, Rezaul Karim (2014) noticed higher per cent increase in exchangeable K with added K compared to initial content at 60 days after incubation in higher clay fraction soils of North eastern barind tract, Bangladesh.

Higher amount of exchangeable K compared to initial content in K solubilizer alone and Fert. K + K solubilizer treatments in high available K soils compared to the low and medium available K soils, but per cent increase over the initial content was higher in low and medium available- K soils. This might be due to change in clay mineralogy as high available K soils have illite clay minerals which released more fixed K or non-exchangeable K by the activity of organic acids released by the K solubilizer (*Frateuria aurantia*) compared to low and medium available K soils dominated by kaolinite mineral. Lower fixed K in low and medium available K soils was due to lower surface charge density, but the per cent increase over the initial content was higher due to lower initial exchangeable K in these soils. These findings are in conformity with the results of Srinivasa rao et al. (1997) who reported dislodging of interlayer K by organic acids and it was attributed to organic ligands forming metal-organic complexes, which accelerate mineral decomposition and weakening of surrounding OH groups by protonation and also found that Alfisols showed lower amount of non-exchangeable K release relative to Vertisols as these soils have lower clay as well as illite content.

3.2.4 Non-Exchangeable K

In the present investigation, irrespective of whether soils received fertiliser potassium (K), potassium-solubilising inoculants, or their combined application, a decline in non-exchangeable K was observed at 15 days after incubation (DAI). This decrease may be attributed to the release of potassium from the non-exchangeable pool into the water-soluble and exchangeable fractions. However, at 60 and 120 DAI, an increase in non-exchangeable K was recorded, accompanied by a corresponding reduction in water-soluble and exchangeable K. This behaviour is likely explained by the dynamic equilibrium governing soil potassium fractions. During the initial phase of incubation, the equilibrium appears to shift towards the more readily available forms (water-soluble and exchangeable K), whereas at later stages, a reverse shift occurs towards non-exchangeable and lattice-bound forms, resulting in an apparent increase in the non-exchangeable K fraction. Similar observations have been reported by Elbaalawy et al. (2016), who identified a significant positive correlation between available K (water-soluble and exchangeable K) and non-exchangeable K, thereby confirming the existence of equilibrium relationships among these forms. Likewise, exchangeable K has been shown to correlate positively and significantly with non-exchangeable K, indicating that depletion in exchangeable K is replenished through the release of potassium from non-exchangeable reserves in soils across different agro-ecological sub-regions of Northern India.

There was a decreasing trend of non-exchangeable K up to 15 DAI in low and medium available K soils treated with Fert. K + K solubilizer, thereafter, it increased gradually with increase in incubation period in all the soils studied, which was attributed to fixation of water soluble and exchangeable K. But, per cent increase over the initial content differed with different soils, because higher exchangeable K was fixed in medium and high available K soils due to changes in clay mineralogy and clay content in theses soils. But, per cent increase over initial content was higher in low and medium available K soils due to lower initial values of non-exchangeable K but, the actual fixation was higher in high available K soils due to higher surface charge density due to presence of illite clay minerals. Similarly, Basak and Biswas (2009) found a decrease in non-exchangeable K at the initial growth stage of sudan grass up to 60 days grown in two Alfisols of Bhubaneshwar and Hazaribag soils, thereafter, gradual increase in the non-exchange K was recorded in treatment receiving waste mica and potassium solubilizing microorganism (*Bacillus mucilaginosus*) and it was attributed to K uptake by sudan grass at the initial stages and at later stages fixation of water soluble and exchangeable K to unavailable K. Among the two soils, larger non exchangeable K was recorded in Alfisols from Hazaribag and it was attributed to presence of larger amount of illite/mica as well as higher clay content in this soil.

4. Conclusion

The study revealed that application of K fertilizer and K solubilizer either alone or in combination has increased the water soluble and exchangeable potassium with concomitantly decrease in non-exchangeable forms over the initial value the amount of water soluble and exchangeable K in the different treatments followed the sequence Fert. K + K- solubilizer > Fertilizer-K > K- solubilizer > Control treatments.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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