Comparative Analysis of Extractants and Temperature on Desorption of Non-Exchangeable Potassium under Different Land Uses of the North Western Himalayas

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Abstract

For a better comprehension of ecosystem sustainability, the assessment of every contributory factor is of paramount significance. The non-exchangeable potassium desorption was examined in the respective samples of all the soils at three separate incubation temperatures, viz. 20, 30, and 40°C, making use of two distinct organic acids: 0.01 M oxalic acid and 0.01 M citric acid under different land uses of the temperate lesser Himalayas. The appraisal of various physico-chemical properties revealed a textural class of Sandy Clay Loam to Clay Loam under the examined land uses. The soil reaction was neutral to slightly alkaline with a pH range of 6.60–7.57. A maximum pH of 7.57 was marked in the wasteland soil and the lowest value was observed in pasture soil. A fairly high content of organic carbon (OC) was noticed, with a range of 0.46–2.03% under different land uses. Higher amounts of non-exchangeable potassium (K+) were noted to be released through oxalic acid as an extractant, followed by citric acid. The amount of non-exchangeable K+ desorbed at three different temperatures differed significantly, with maximum desorption at 40°C followed by 30°C and least at 20°C. Regardless of the temperature of incubation and extractant evaluated, non-exchangeable K+ desorption amounts were marked to be maximum under agricultural irrigated soils, and lowest was noticed from pasture soils. The Elovich equation/model was marked to be best for both treated and untreated soils under different land uses at different temperatures and extractants among different kinetic models evaluated, followed by the power function and parabolic diffusion law as elucidated by the highest values of coefficient of determination (R^2) and the least values of corresponding estimates standard error (S.E.). In describing the desorption kinetics, even though the type of kinetic model remained mostly unaffected, the values of b were observed to increase in K-treated soils, i.e., from 0.308 cmol K+ kg^{-1} to K-saturation (100 cmol K+ kg^{-1}) and with an increase in temperature from 20 to 40°C, indicating a pronounced release of non-exchangeable potassium in K-treated soils at higher temperatures.

Keywords: Potassium desorption, Temperature, Extractants, Land Use, Himalayas.

Highlights

- The desorption of non-exchangeable potassium was appraised using different extractants and temperatures under different land uses of the district Kupwara.
- The non-exchangeable potassium desorption was marked higher using oxalic acid as an extractant.
- The desorption of non-exchangeable potassium at 40°C exhibited an edge over 30 and 20°C.
- The agriculture irrigated land use system exhibited higher amounts of non-exchangeable potassium desorption, while the lowest was observed in Pasture soils.
- The desorption process was observed to follow the Elovich equation, followed by the power function and parabolic diffusion model.

Introduction

Certain poor agricultural management techniques have led to the depletion of soil fertility and widespread environmental degradation on a global scale. This calls for immediate and focused efforts to establish sustainable agricultural production systems. Despite agricultural activities utilizing 37% of the total land area of Earth, the comprehensive challenge of achieving sustainable food production persists (Chen *et al.*, 2018). Issues include soil and land degradation, the impact of climate change, including rising sea levels, and the rapid reduction of available arable land. This challenge is exacerbated by projected population growth, estimated to arrive at 9.8 ± 1 billion by 2050 and 11.2 ± 1 billion by 2100 (Olowe, 2021). This predicament necessitates the immediate adoption of sustainable agricultural intensification practices to fulfill our requirements for food, fuel, and fiber. Land use type and management practices pose remarkable imprints on the dynamics of soil characteristics and reflect the interaction of anthropogenic stimulus with the ecosphere (Assefa *et al.*, 2020). Comprehensive information is needed regarding the imprints of land use fluctuations on soil characteristics. This information portrays an impending role in effective environmental management and ensuring the sustainable utilization of land resources. By addressing these concerns and implementing appropriate strategies, we can significantly reduce the extent of soil and land degradation. This allows us to sustain the requirements of the current as well as future generations while safeguarding environmental health.

The kinetic studies of the processes prevalent in soil furnish evidence on the dynamics of reactions vis-à-vis their time scale existing amid different constituents of soil, viz., clay content, and applied fertilizers, reflecting the accessibility of the latter (Wani, 2012). The potassium status inherited by the soil is mostly governed by the non-exchangeable potassium desorption rate and amount prevalent in that specified soil

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(Benipal and Pasricha, 2002). The convenience with which non-exchangeable potassium is delivered from the reservoirs indicates the supplementation power of soil potassium to the crops. Land use practices significantly influence potassium (K+) dynamics in soil, affecting its availability and distribution. The distribution of total soil K+ in surface soil layers is primarily governed by soil formation processes, including parent material and soil types, while exchangeable and available K+ forms are mostly influenced by land use changes (Azadi and Shakeri, 2020). In addition, the potassium desorption in soils is dependent on various factors such as the concentration of potassium, temperature, and competing ions (Moritsuka et al., 2004; Schneider et al., 2013). The temperature fluctuations pose prominent imprints on the exchange reactions of potassium (Blank, 2010). To get familiar with the energetics of the soil reactions, the kinetics of the potassium desorption reactions at distinct temperatures is accomplished. These studies pave the way for the assessment of different management practices concerning their efficacy for the facilitation of potassium release (Pasricha and Bansal, 2001). The annual temperature in the Kashmir valley has been opined to vary from about -10 to 35°C. Kupwara district has been marked to record the highest ~1.3°C increase in maximum temperature (Zaz et al., 2019).

For a better comprehension of ecosystem sustainability, the assessment of every contributory factor is of paramount significance. The evaluation of different salts and organic acid solutions for the determination of non-exchangeable potassium desorption mimics the effect of plant root extraction from the soils (Das et al., 2022). The nature of organic acids predominant in the soil environment, principally in the zones where the intensity of biological activity is quite high, primarily affects the potassium desorption dynamics from different potassium-containing minerals (Wani, 2012). Thus, the competence of different extractants for the apprehension of plant-available potassium under different management systems is of the need of the hour. Given this, the current investigation hypothesized that the desorption of non-exchangeable K+ from soils varies significantly with changes in temperature, type of chemical extractant, and land use practices. Consequently, the current investigation appraised the effect of temperature on potassium desorption under different land uses using different chemical extractants.

MATERIALS AND METHODS

Study area
The area of investigation is situated at an altitude of 5300 ft (above the main sea level) and falls in the north-west region of Kashmir. District Kupwara falls in the North-West expanse of Kashmir, situated approximately 90 km from Srinagar, and possesses a total geographical area of 2379 km^2. It is surrounded in the South and East by district Baramulla and in the North and West by the line of control, partitioning it with district Muzaffarabad. The district possessing diverse land configurations exhibits a hilly terrain, where the parts encircled in the south are plain, and the areas covering the west, north, and east are hilly. The location of the Kupwara district lies between 34.3 to 35.5°N and 73.4 and 74.9 °E, enveloped by abundant forests, mountain slopes, and snow-capped peaks across three borders. Additionally, the soils of Kupwara are marked to exhibit a silty loam textural class and are categorized under the order Alfisols and Mollisols on taxonomical grounds (Khan et al., 2023).

Sample collection and analysis
Surface samples as composites were gathered at a depth of 0–20 cm from distinct land uses of the district Kupwara, differing in their properties and each of them reflecting a specific land use. However, among the appraised land uses, surface (0–20 cm) and sub-surface 20–40 cm soil samples were acquired from horticultural land use. The description of acquired soil samples from different land uses is portrayed in Table 1. The procured soil samples were subjected to air drying, subsequently crushed using a mortar and pestle, and then passed through a 2 mm sieve for further analysis. Estimation of soil pH was accomplished in 1: 2.5 -soil : water suspension using a digital glass electrode pH meter (Jackson, 1967). The appraisal of cation exchange capacity was performed following the approach of Rhoades (1982) and calcium carbonate by Puri (1930). The execution of the rapid titration method described by Walkley and Black (1934) was executed for the appraisal of soil organic carbon.

Potassium Desorption Study
The non-exchangeable potassium desorption was examined in the respective samples of all the soils, in duplicate, at three separate incubation temperatures, viz., 20, 30, and 40°C, making use of two organic acids: 0.01 M oxalic acid and 0.01 M citric acid. Equilibration of the soil samples (10 g each) was done using 50 mL each of 0, 0.308 cmol K+ kg^{-1} soil and with a K+ solution

Table 1: Description of acquired soil samples from different land uses

S. No.	Land use	Location	Latitude (° N)	Longitude (° E)
1.	Agriculture Irrigated	Chandigam	34°29′	74°22′
		Badibera	34°32′	74°22′
		Kuligam	34°33′	74°25′
		Gugloosa	34°49′	74°15′
		Sogam	34°30′	74°22′
		Langate	34°25′	74°17′
		Nagri	34°28′	74°15′
		Mawer	34°21′	74°16′
		Kralpora	34°30′	74°06′
		Kulangam	34°25′	74°18′
2.	Rainfed Agriculture	Sogam	34°30′	74°22′
		Kulangam	34°25′	74°18′
		Langate	34°25′	74°17′
		Gugloosa	34°49′	74°15′
		Badibera	34°32′	74°22′
		Nagri	34°28′	74°15′
		Kuligam	34°33′	74°25′
		Kralpora	34°30′	74°06′
		Mawer	34°21′	74°16′
		Chandigam	34°29′	74°22′
3.	Horticulture	Kuligam	34°33′	74°25′
		Nagri	34°28′	74°15′
		Chandigam	34°29′	74°22′
		Gugloosa	34°49′	74°15′
		Sogam	34°30′	74°22′
		Mawer	34°21′	74°16′
		Kulangam	34°25′	74°18′
		Badibera	34°32′	74°22′
		Langate	34°25′	74°17′
		Kralpora	34°30′	74°06′
4.	Pasture	Badibera	34°32′	74°22′
		Kulangam	34°25′	74°18′
		Langate	34°25′	74°17′
		Gugloosa	34°49′	74°15′
		Sogam	34°30′	74°22′
		Chandigam	34°29′	74°22′
		Kuligam	34°33′	74°25′
		Kralpora	34°30′	74°06′
5.	Wasteland	Mawer	34°21′	74°16′
		Nagri	34°28′	74°15′
		Mawer	34°21′	74°16′
		Kalaroos	34°31′	74°15′
		Kuligam	34°33′	74°25′
		Badibera	34°32′	74°22′
		Langate	34°25′	74°17′
		Gugloosa	34°49′	74°15′
		Sogam	34°30′	74°22′
		Batargam	34°53′	74°23′
		Villagam	34°40′	74°28′
		Kralpora	34°30′	74°06′

sufficient for saturation of soil exchange complexes, i.e., 100 cmol K+ kg^{-1}, for 5 days at three distinct incubation temperatures, viz., 20, 30 and 40°C with intermittent shaking. Incubation of these samples was performed at the requisite temperature ± 1°C in an atomic BOD incubator. After equilibration of soil samples, centrifugation of the suspensions was carried out in a temperature-oriented centrifuge and provided with one washing of 50 mL 1 N ammonium acetate in order to destitute them of water-soluble as well as exchangeable potassium. The soils devoid of ammonium acetate potassium were taken for extraction with 50 ml each of 0.01 M oxalic and citric acid solutions, and centrifugation of samples was done, followed by the analysis of the supernatant solution for the determination of potassium by flame photometry. The experimental kinetic data were recorded at 0, 1, 2, 4, 12, 24, 36, 48, 60, 96, and 192 hours (hr) and the data acquired were fitted employing five different kinetic models, viz. First-order kinetic equation, parabolic diffusion law, Elovich equation, zero-order equation, and Power function equation.

Statistical Analysis

The observations recorded were statistically analyzed, executing standard procedures in accordance with Gomez and Gomez (1984). The effect of Land Use on various soil properties and potassium desorption was evaluated using Analysis of Variance (ANOVA) at a 5% significance level (p ≤ 0.05). For modeling, the least squares regression equation was employed. Models possessing the least standard error (S.E.) and the highest coefficient of determination (R^2) were chosen as the criteria of goodness of fit. The statistical analysis of the acquired data was performed using RStudio and Origin Pro software.

RESULTS AND DISCUSSION

Physico-chemical properties of soils

The mean values pertaining to the soil physico-chemical characteristics are portrayed in Table 2. The inferences revealed that the textural classes exhibited a variation from Sandy Clay Loam to Clay Loam under the examined land uses. The soil

Table 2: Soil Physico-chemical characteristics under different land use systems of district Kupwara

Land uses	pH	OC	CaCO$_3$	CEC	Sand	Silt	Clay
	(1:2.5)	(%)	(%)	(cmol (p$^+$) kg^{-1})		(%)	
Agri-irrigated	7.31^b	0.88^d	1.20^d	13.88^d	36.79^d	29.06^f	34.02^a
Rainfed agriculture	7.03^d	0.83^e	1.61^c	12.97^e	36.59^e	41.84^b	21.07^d
Hort (0–20 cm)	6.75^e	1.02^b	1.05^f	15.05^c	37.20^c	41.06^c	21.46^c
Hort (20–40 cm)	7.11^c	0.91^c	1.07^e	16.70^b	35.02^f	42.02^a	22.84^b
Pasture	6.60^f	2.03^a	1.92^b	18.56^a	42.82^a	36.84^e	20.43^e
Wasteland	7.57^a	0.46^f	2.59^a	9.34^f	42.06^b	37.47^d	20.04^f

Values prevalent in the same column that are tailed by different lowercase letters exhibit a significant difference at *p = 0.05*

reaction was observed to fall under the neutral to slightly alkaline class with a pH range of 6.60-7.57. A maximum pH of 7.57 was marked in the wasteland soil and the lowest value was observed in pasture soil. Maqbool *et al.* (2017), while performing an analysis of some Kashmir soils, reported a pH range of 5.45-8.50 under different land uses of the district Ganderbal. These findings align with the observations put forward by Bashir *et al.* (2016). A fairly high content of organic carbon (OC) was noticed with a range of 0.46-2.03% under different land uses. A maximum of 2.03% organic carbon content was observed in pasture soils and a minimum of 0.46% was observed in wasteland soils. The elevated contents of organic carbon might be attributed to the improved biomass influx into the pasture soils and less biomass incorporation in the wasteland soils due to sparse vegetative cover. In addition, the low-temperature values as well as slow mineralization rates account for the amplified contents of organic carbon, while rapid mineralization rates and subsequent carbon loss from cultivated soil account for the low organic carbon values in respective land uses (Chauhan *et al.*, 2014). The calcium carbonate content varied from 1.05 - 2.59% under the appraised land uses in alignment with the trend wasteland > pasture > agriculture un-irrigated > agriculture irrigated >horticulture, exhibiting the mean values 2.59, 1.92, 1.61, 1.20, and 1.05%, respectively. The range of cation exchange capacity in the respective land uses was observed to vary from 9.34 cmol$_c$ kg^{-1} to 18.56 cmol$_c$ kg^{-1} under different land uses with the highest mean value in pasture soils (18.56 cmol$_c$ kg^{-1}) and that of lowest in wastelands (9.34 cmol$_c$ kg^{-1}), owing it to the elevated contents of organic matter in pasture soils and vice versa in wasteland soils. These observations are corroborating the observations of Wani *et al.* (2010), Pal *et al.* (2013), Ramzan *et al.,* (2014) and Bashir *et al.* (2016).

Potassium Desorption Study

Non-exchangeable potassium desorption was characterized from K-untreated and treated soils at three different temperatures using two organic extractants, viz., 0.01 M citric acid and 0.01M oxalic acid, at various times of incubation. The results revealed that as the temperature of incubation increased, non-exchangeable K+ desorption was realized to increase in all the examined soils of the appraised land uses. The proportion of K+ desorbed was noticed to be maximum at 40 and 30°C, followed by 20°C (Fig. 1). Further, it has been revealed that potassium desorption significantly differed in potassium-treated and untreated soils, with greater potassium release in potassium-treated soils. A marked increase in the desorption of non-exchangeable potassium has been observed while increasing the K+ treatment from 0.308 cmol$_c$ kg^{-1} soil to K-saturation (100 cmol$_c$ kg^{-1}). These findings are further supported by Bhat (2009). The highest release rate of K+ in forest and garden land uses with CaCl$_2$ and oxalic acid extractants might be due to the high NEK, CEC, clay content (especially smectite), and organic matter (Azadi *et al.*, 2024).

Between the two extractants, 0.01M oxalic was found to extract a higher proportion of non- exchangeable potassium in all the appraised experimental soils succeeded by 0.01 M citric acid (Fig. 2). The difference in extraction media is accredited to the exhibition of higher magnitude of dissociated H$^+$ ions and organic ligands that can form metal complexes thus enhancing mineral decomposition and weakening of surface hydroxyl (OH$^-$) groups by protonation. Similar results for higher amounts of potassium desorption by oxalic acid were reported by Jalali and Zarbi (2006) and Bhat (2009). The non-exchangeable K+ desorption of surface soils in response to the employment of two different extractants exhibited an edge over subsurface soils. CaCl$_2$ and oxalic acid were marked to desorb higher contents of K+ in surface soils (22%) in contrast to the sub-surface soils (28%) from non-exchangeable sites (Zareian *et al.*, 2018). Wani (2012), while examining the influence of oxalic acid on potassium desorption kinetics, put forward that the solution of oxalic acid exhibiting low pH had the ability to extract more potassium, the impact of which was enhanced at lower pH.

The inferences from figures 1 and 2 elucidate that regardless of the temperature of incubation and extractant evaluated, non-exchangeable potassium desorption amounts were remarked to be maximum under agricultural irrigated soils and lowest were noticed from pasture soils. The gradient in potassium release might be attributed to the difference in the mineralogical composition of the respective soils at different locations, as soil development exhibits a pronounced impact on potassium release in soil. Similar dependence has been put forward by Jalali and Khanlari (2014) who reported a maximum amount of potassium release in soils enclosed with leafy vegetables and a minimum potassium release in soils engaged by pastures.

Kinetic Modeling

The Elovich equation/model was marked to be best for both treated and untreated soils under different land uses

at different temperatures and extractants among different kinetic models evaluated, followed by a power function, and parabolic diffusion law as elucidated by the highest values of coefficient of determination (R^2) in hand with the least values of corresponding estimates S.E (Table 3). The rate constants for potassium desorption were computed for the respective soils under different land uses at different temperatures and extractants following the zero-order, parabolic diffusion, power function, first-order, and Elovich models/equations. Rather than presenting the description for all soils (i.e soils treated and untreated with K+, temperatures, and different extractants),

the best fit kinetic equations (Elovich model) acquired under different land use systems with operating conditions yielding higher potassium release (K-saturated soil at 40 °C with oxalic acid extractant) have been presented in Fig. 3. The values of a and b parameters for the kinetic model best describing potassium desorption behaviour under different land uses have been presented in Tables 4 and 5. Parameter b, representing the potassium release, was found to be less than one in K- K-un-treated soils at different temperatures and extractants, reflecting a decreasing rate of potassium desorption. The values of b were observed to increase in K-treated soils, i.e., from 0.308 cmol K+
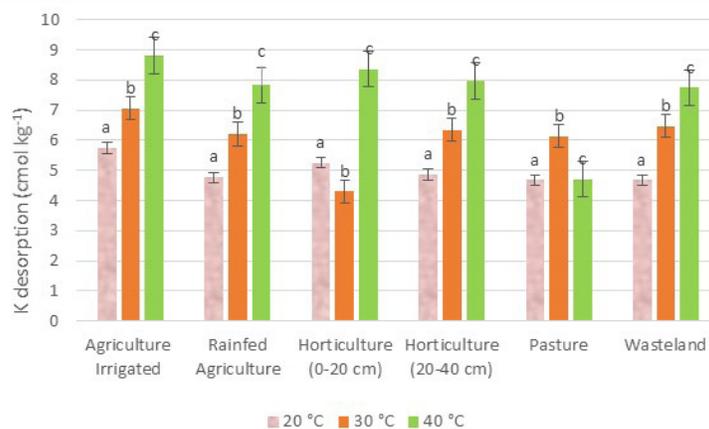

Fig. 1: Effect of different temperatures on desorbed potassium (cmol kg^{-1}) under different land uses
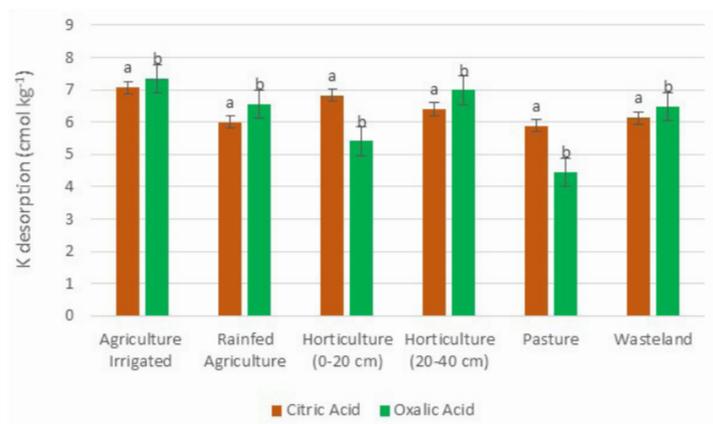

Fig. 2: Effect of extractants on desorbed potassium (cmol kg^{-1}) under different land uses

Table 3: Relative performance of different kinetic models (R^2-value and SE) describing oxalic acid extractable non-exchangeable potassium data at 40°C in K-saturated soils under different land uses

| Land use | Kinetic Models | | | | | | | | | |
| | First order | | Zero order | | Power function | | Parabolic diffusion | | Elovich | |
	R^2	S. E	R^2	S. E	R^2	S. E	R^2	S. E	R^2	S. E
Agriculture Irrigated	0.40	24.22	0.39	257.6	0.80	26.47	0.70	29.91	0.90	2.19
Rainfed Agriculture	0.48	22.06	0.47	704.3	0.82	24.29	0.77	27.56	0.93	1.75
Horticulture 0–20 cm	0.40	23.27	0.40	246.7	0.82	25.50	0.71	28.86	0.90	2.35
Horticulture 20–40 cm	0.46	22.46	0.46	239.0	0.81	24.70	0.76	28.01	0.93	1.78
Pasture	0.47	21.80	0.46	232.4	0.82	24.02	0.76	27.29	0.93	1.82
Wasteland	0.47	21.68	0.46	231.4	0.82	23.91	0.76	27.17	0.93	1.82

(a) Agriculture Irrigated   (b) Rainfed Agriculture   (c) Horticultural (0 - 20 cm)

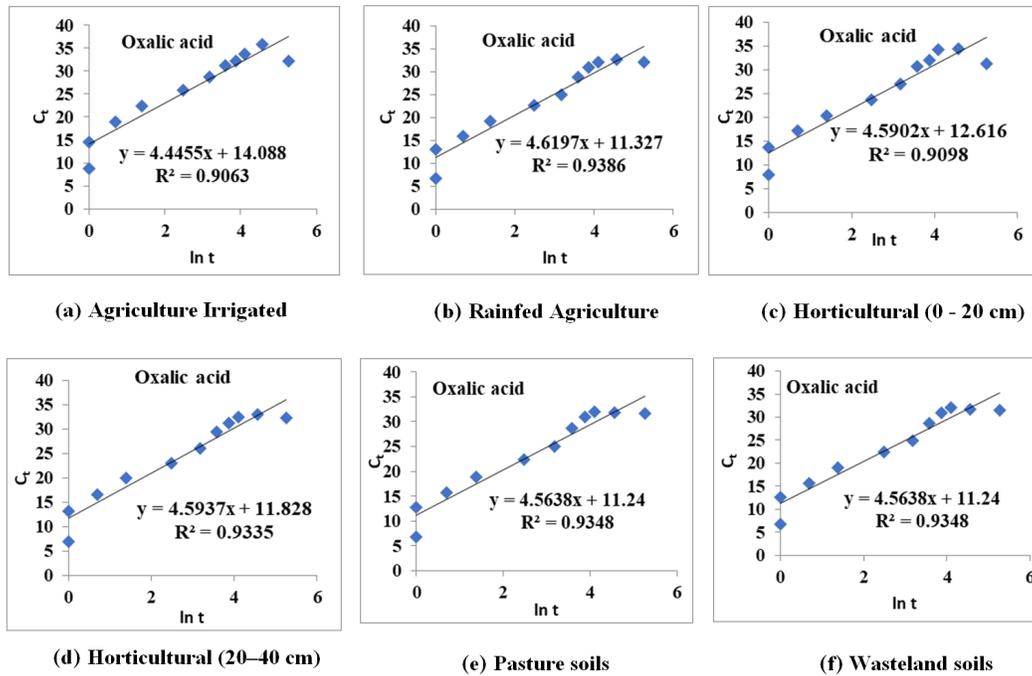(d) Horticultural (20–40 cm)   (e) Pasture soils   (f) Wasteland soils

Fig. 3: Best fit kinetic equations (K-saturated soils at 40°C and oxalic acid extractant) under different land uses

Table 4: Value of 'a' and 'b' parameters of the kinetic model best describing citric acid extractable non-exchangeable K+ desorption behaviors under different temperatures

| Land Use | Temperature (°C) | Untreated (cmol K+ kg^{-1} soil) | | Treated | | | |
| | | | | (0.308 cmol K+ kg^{-1} soil) | | (K-saturated) | |
		A	b	a	b	a	b
Agricultural Irrigated	20	0.041	0.036	0.094	0.101	3.802	6.330
Rainfed Agriculture	20	0.031	0.021	0.074	0.086	3.254	4.756
Horticulture 0-20cm	20	0.033	0.035	0.093	0.092	3.613	4.965
Horticulture 20-40cm	20	0.031	0.024	0.073	0.094	3.381	4.653
Pasture	20	0.028	0.018	0.072	0.074	3.187	4.688
Wasteland	20	0.029	0.013	0.073	0.069	3.179	4.687
Agricultural Irrigated	30	0.073	0.043	0.121	0.170	4.605	8.518
Rainfed Agriculture	30	0.046	0.036	0.099	0.143	4.408	5.885
Horticulture 0-20cm	30	0.046	0.051	0.098	0.169	3.585	7.603
Horticulture 20-40cm	30	0.049	0.035	0.098	0.149	4.564	5.894
Pasture	30	0.043	0.034	0.095	0.140	4.360	5.666
Wasteland	30	0.042	0.032	0.094	0.136	4.468	5.509
Agricultural Irrigated	40	0.124	0.085	0.285	0.288	4.439	12.09
Rainfed Agriculture	40	0.077	0.067	0.220	0.275	4.277	9.756
Horticulture 0-20cm	40	0.078	0.084	0.231	0.277	4.314	11.12
Horticulture 20-40cm	40	0.077	0.072	0.220	0.284	4.007	10.850
Pasture	40	0.075	0.061	0.221	0.261	4.231	9.546
Wasteland	40	0.074	0.056	0.221	0.258	4.225	9.533

Table 5: Value of 'a' and 'b' parameters of the kinetic model best describing oxalic acid extractable non-exchangeable K+ desorption behaviors under different temperatures

Land Use	Temperature (°C)	Untreated (cmol K+ kg⁻¹ soil)		Treated (0.308 cmol K+ kg⁻¹ soil)		(K-saturated)	
		A	b	a	B	a	b
Agricultural Irrigated	20	0.062	0.041	0.101	0.135	4.039	6.310
Rainfed Agriculture	20	0.046	0.028	0.084	0.122	3.597	4.888
Horticulture 0–20 cm	20	0.051	0.034	0.107	0.109	3.724	5.529
Horticulture 20–40 cm	20	0.046	0.031	0.084	0.127	3.610	5.108
Pasture	20	0.045	0.020	0.082	0.120	4.563	11.24
Wasteland	20	0.044	0.018	0.081	0.117	3.575	4.719
Agricultural Irrigated	30	0.088	0.073	0.100	0.166	4.194	9.094
Rainfed Agriculture	30	0.073	0.034	0.098	0.150	4.363	6.984
Horticulture 0–20 cm	30	0.055	0.085	0.098	0.169	4.189	7.912
Horticulture 20–40cm	30	0.072	0.040	0.099	0.152	4.422	7.186
Pasture	30	0.060	0.041	0.100	0.143	4.418	6.742
Wasteland	30	0.059	0.040	0.099	0.141	4.422	6.721
Agricultural Irrigated	40	0.163	0.070	0.310	0.366	4.445	14.080
Rainfed Agriculture	40	0.117	0.089	0.248	0.272	4.619	11.32
Horticulture 0–20 cm	40	0.091	0.134	0.224	0.413	4.590	12.61
Horticulture 20–40 cm	40	0.120	0.090	0.245	0.284	4.593	11.82
Pasture	40	0.110	0.085	0.249	0.263	4.563	11.24
Wasteland	40	0.105	0.087	0.250	0.255	4.538	11.21

kg⁻¹ to K-saturation (100 cmol K+ kg⁻¹) and with an increase in temperature from 20 to 40°C, indicating a pronounced delivery of non-exchangeable potassium in K-treated soils at higher temperatures. Employing different mathematical models for determining the non-exchangeable potassium desorption rates from the profoundly cultivated soils of western Iran, it was concluded based on a greater R-squared value, along with values (least) obtained for estimates' S.E., that the first order as well as the power function models best fit the kinetic data of potassium release. Also, diffusion-controlled exchange can be signified, as the parabolic diffusion equation also described the data satisfactorily (Jalali, 2005). Parameterization of potassium release in reference to time dependency was done while evaluating zero-order, Elovich, first-order, and parabolic diffusion models. During the investigation of Ultisols, an increase in the release rates of potassium was observed after using the citrate solution as an extraction medium. The Elovich model was marked to fit the experimental data of potassium desorption kinetics most effectively. The edge of potassium desorption rates in the case of ultisols was attributed to the conveyance of non-exchangeable potassium to the extracting solution; however, in studies of fractions of Oxisols, the exchangeable potassium depicted the primary source of potassium (Silva *et al.,* 2008). These observations further align with the experimental outcomes of Ghiri *et al.* (2012), who documented a cumulative K release of 175 to 723, 35 to 128, and 71 to 146 mg kg⁻¹ for clay, silt and sand

fractions, respectively. Sokolova *et al.,* (2018) revealed that the desorption of the easily exchangeable K is adequately described by the zero-order equation of reaction, and the reaction rate constants describing the desorption of non-exchangeable and easily exchangeable K+ from chernozems were three to five times higher than those for soddy-podzolic soils and other soils of humid regions.

CONCLUSION AND FUTURE PROSPECTS

The ability of soils to desorb potassium under different treatments aids in the evaluation of potassium accessibility to crops. Temperature plays an important role in the desorption of the non-exchangeable fraction of potassium and replenishes the accessible potassium depleted by crops. Given this, we have to apply potassium fertilizers more in *Rabi* crops than *Kharif* crops as the desorption of non-exchangeable potassium increased with an increment in temperature from 20 to 40°C in the examined soils of different land uses. Among the extractants, oxalic acid was noted to extract higher amounts of non-exchangeable potassium, followed by citric acid. In describing the desorption kinetics, even though the type of kinetic model remained mostly unaffected, the values of b were observed to increase in K-treated soils, i.e., from 0.308 cmol K+ kg⁻¹ to K-saturation (100 cmol K+ kg⁻¹) and with an increase in temperature from 20 to 40°C, indicating a pronounced release of non-exchangeable potassium in K-treated soils at higher temperatures.

To enhance the understanding of non-exchangeable K+ dynamics under diverse land uses and environmental conditions, it is imperative to consider a wider range of extractants, including both organic and inorganic acids, to better simulate the natural root zone chemistry. In addition, investigating other land use types such as alpine pastures and agroforestry would provide a more comprehensive perspective on potassium desorption across different landscapes of the North-western Himalayas. Advanced mineralogical characterization, such as X-ray diffraction (XRD) and scanning electron microscopy are recommended to elucidate the mineralogical composition and its influence on potassium retention and release.

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AUTHOR CONTRIBUTIONS

Conceptualization, Aanisa Manzoor Shah, and Shaista Nazir; methodology, Shaista Nazir, Inayat M Khan and Yasir Hanif Mir; software, Fehim Jeelani Wani and Yasir Hanif Mir; validation, Shaista Nazir, Javid A Bhat; formal investigation, Aanisa Manzoor Shah and Yasir Hanif Mir; resources, Javid A Bhat and Tahir A Sheikh; data curation, Aanisa Manzoor Shah, Fehim Jeelani Wani, Yasir Hanif Mir and Bisma Jan; writing—original draft preparation, Aanisa Manzoor Shah, Zarka Nabi, and Rifat-Un Nissa; writing—review and editing, Shaista Nazir, Yasir Hanif Mir, Bisma Jan, Tsering Dolker; supervision, Shaista Nazir, and Rehana Rasool. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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