



Impact of different land uses on potassium forms and soil properties: the case of southwestern Iran

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Abstract

The primary focus of this research was to evaluate the influence of various land utilization patterns on the potassium levels and fertility attributes of the soil in Kohgiluyeh and Boyer Ahmad Province, located in the southwest region of Iran. This prioritization is essential due to the rising population and the need to meet the food requirements of the people. Hence, this study used the release of potassium (K) by using CaCl_2 and oxalic acid 0.01 M as extractants. Additionally, the study measured the capacity of K fixation in calcareous soils under different land-use systems, specifically wheat, garden, forest, fallow fields, and pastures. The K release and fixation capacities were assessed in both surface and sub-surface soil layers using alternative wet, dry, and normal treatment methods. The results revealed that the median soil pH across the studied land uses was 7.4, ranging from 6.5 to 7.7. The highest pH was observed in the wheat land use, while the garden land use had the lowest pH. In terms of organic carbon content, the studied soils exhibited variations ranging from 0.9 to 1.94%. These differences can be attributed to variances in mineral structures among different soil types. To mitigate the loss of fertilizer sources and prevent groundwater contamination, it is recommended to implement a combination of commercial fertilizers with targeted micronutrients. Additionally, adopting soil conservation techniques and encouraging long-term fallow practices can also contribute to these efforts. In conclusion, the findings emphasize the importance of implementing appropriate soil management strategies to enhance nutrient availability, minimize environmental risks, and sustain agricultural productivity.

Keywords Land use · Potassium release and fixation · Wetting and drying · Extractant

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1 Introduction

One of the essential elements needed by plants is potassium (K). Among plant nutrients, potassium (K) exhibits superior performance, especially in a range of physiological processes essential for the overall quality, development, and ability of all crops to withstand stress (Rekha et al., 2020). However, since the effect of potassium on the role of nitrogen (N) and phosphorus (P) in increasing grain production is gradual, potassium has received less attention, especially in enriched soils (Tran et al., 2018).

K is regarded as the seventh most prevalent and abundant element globally and constitutes approximately 2.1–2.3% of the Earth's crust (Mikkelsen & Roberts, 2021). Therefore, there are many sources of K in the soil (Murrell et al., 2021). Nonetheless, numerous significant agricultural regions worldwide suffer from insufficient K availability. This deficiency encompasses approximately 75% of China's paddy soil and about two-thirds of South Australia's wheat belt (Ma et al., 2019). K amount is often naturally low in saline or acidic, sandy, and loamy soils. In addition, K is considered a limiting element in intensive agricultural systems, especially in soils with coarse or organic textures. Less application of K fertilizer under unstable fertilization conditions may lead to a significant reduction in available K sources in soil and, thus, soil fertility (Murrell et al., 2021). According to Volenec et al. (2021), in comparison to nitrogen (N) and phosphorus (P), potassium (K) fertilizers are administered at a significantly reduced dosage, and less than 50% of the K depleted by crops is replenished. K deficiency in southwestern Iran is a serious problem. Because of the non-application of K fertilizers, non-exchangeable K is depleted from these soils. Therefore, knowledge about the amount of added and depleted K from the soils can be effective in better management of soil nutrients (Najafi-Ghiri et al., 2019; Shashikumar et al., 2022). Understanding the effects of land use on the quality of different soil types is critical for maintaining and increasing soil fertility and production in sustainable agriculture. Soil quality primarily relies on the soil's reaction to different land uses and diverse management methods in a way that most soil properties and subsequent soil production capacity could be improved by proper management and land-use practices (Lizaga et al., 2019).

The amount of K in most agricultural soils (at a depth of about 0.2 m), according to Zörb et al. (2014), is between 10 and 20 g. Depending on the type of soil, the availability of K varies considerably and is influenced by the physico-chemical features of the soil. To describe the complex dynamics of potassium (K) in soil, it is often categorized into four types depending on its availability to plants, including being soluble in water and capable of being exchanged, essential, and inorganic or forming part of the soil structure. In soil, around 0.1–0.2% and 1–2% of the whole K is delivered by water-soluble K and replaceable K. The amount of K available and unavailable in the plant varies between different soil K pools based on soil types and dynamic equilibrium reactions (Murrell et al., 2021). Soil properties in different agricultural uses are significantly different because of the quantity of potassium in the soil. As a result, some chemical and physical features impact the release and fixation of K in the soil, such as interactions between soil and plants and microbial activity (Bekele, 2018; Murrell et al., 2021).

Biological, physical, and chemical factors related to climate influence the forms of potassium (K) and its equilibrium in the soil, which can be associated with clay mineral composition, surface, dampness, cation trade capacity (CEC), and other soil particle concentrations. Fertilization and farming are important management factors affecting soil's K balance, in addition to these soil characteristics (Golestanifard et al., 2020).

The properties and quality of soil are affected by factors such as changes in land use and management. The growth pattern of the plant and its environment is affected by changes in soil characteristics and processes. In fact, practices of soil management and land-use changes affect soil properties related to soil processes such as leaching, oxidation, mineralization, etc., and thus change soil quality. Land-use change can be a major threat to the soil system (Bekele, 2018). The amounts of K in different soil layers are in balance with each other. K and minerals containing exchangeable K in arid and semi-arid soils are usually sufficient to provide enough K for crops (Boostani et al., 2019).

However, 90–98% of the K in the soil is not instantly absorbed by the plant due to the structure of the crystal lattice. In reality, the quantity of K varies greatly amongst soil types and is determined by the soil's physico-chemical qualities. K fixation of soil minerals, as well as potassium release, also affects K availability. This procedure involves absorbing high K ions at locations in the layers between the silicate plates, such as illite and vermiculite. The amount of K fixed in the soil is related to factors such as soil pH, moisture, stocking density, and mineral type. Montmorillonite, vermiculite, and weathered micas are crucial clay minerals that have a tendency to immobilize potassium (Zörb et al., 2014). Other factors, such as soil moisture, also affect K uptake. Due to the strong affinity between K and clay minerals, the liberation of bound K is exceedingly sluggish, but the immobilization of K is virtually instantaneous (Shakeri & Abtahi, 2020). The uptake or release of potassium within the soil is profoundly impacted by the quality and transparency of potassium presence (Zörb et al., 2014). It seems that the amount of H⁺ in soil response (through soil pH), in addition to natural acids, plays a vital role in the discharge of K from clay minerals. Therefore, increasing soil K and improving plant absorption can be achieved by adjusting soil pH. To optimize the management of K chemical, it is essential to grasp the regulative components of K's discharge from the non-replaceable soil reservoir (Jha et al., 2016). Recent literature has expanded the knowledge on the impact of potassium on soil development and its capacity to absorb water. The use of K mineral fertilizers improves the water-holding capability of the soil and particularly will increase the structural balance of sandy soils. The influence of K's application on soil stability is likely caused by the rise in the concentration of electrolytes in the soil, resulting in the effects and formation of salt crystals (Franzen et al., 2021). According to Meena et al. (2016), elevated concentrations of potassium (K) in the soil could potentially lead to increased micro-shear resistance, providing an explanation for the alterations observed in water retention. In addition, the Mg₂⁺ and Ca₂⁺ cations were easier to maintain in the composition of the soil because the comparative potencies for K, Mg₂, and Ca₂⁺ were separately 1, 27.0, and 3.0, respectively. Increased water retention represents an important part of ensuring soil productivity in limited water areas.

Ghiri and Abtahi (2012) emphasized the vital role of illite and smectite in influencing the activity of potassium ions (K ions) in calcareous soils. Therefore, K fixation and release are dependent on smectite and illite minerals, respectively. Thus, comprehending different effects of land utilization (LU) control on the immobilization and liberation speed of non-replaceable K (NEK) from soil is very important in evaluating the human impact on the release and fixation of soil K. Furthermore, different land uses have significant effects on soil K content.

Although the soils of Iran's south and southwest, which have arid and semi-arid climates, have sufficient soluble and exchangeable K, soil potassium reserves have been decreasing in recent years because of extensive agriculture and limited use of potassium fertilizers. However, information about the K fixation and release rate in various land uses is very limited. Therefore, understanding the K release and fixation mechanisms in

different land uses is of great importance. Moreover, the use of K fertilizers without knowing the mechanism and flow added in different soils may raise questions that need to be addressed. The calcareous soils, compared to other soils, especially those in rainfed areas, have a high buffering property. Hence, the outcomes observed in different regions cannot be universally applied to these specific areas. This is due to the lack of a comprehensive study on the impact of land utilization (LU) on the rate of K discharge and immobilization in carbonate soils. Furthermore, considering the unique weather patterns in Kohgiluyeh and Boyer Ahmad Province and diverse land utilization methods, there has been no previous investigation conducted on the alterations in soil characteristics and potassium forms in different land uses. Consequently, the current research was undertaken with the subsequent aims: (1) to assess the influences of various types of land uses on organic matter content that could affect K release and fixation and (2) to explore whether different land uses affect the quantity and quality of soil minerals.

Linked to the study objectives, this study attempts to answer the following questions:

- 1 Are K forms the same in different land uses?
- 2 Which soil property is most effective on K release and fixation?

This study explores the novel aspects of K dynamics in calcareous soils under different land use systems. While K release and fixation capacities have been extensively studied, our research provides novel insights by utilizing CaCl_2 and oxalic acid 0.01 M as extractants to assess K release. Additionally, we measure the K fixation capacity in both surface and subsurface soil layers. The investigation encompasses a range of land-use systems, including wheat, garden, forest, fallow fields, and pastures, which allow for a comprehensive understanding of K dynamics across various agricultural practices. The results of this investigation have noteworthy consequences for sustainable land administration, emphasizing the need for tailored soil management strategies to enhance nutrient availability and mitigate environmental risks. Moreover, we recognize the constraints of the examination and offer recommendations for future research avenues to enhance our comprehension of soil productivity and nutrient fluctuations. Additionally, the findings of this investigation hold significance and practicality in the management and prediction of unwanted alterations resulting from alterations in land use in comparable regions within Iran and globally.

2 Methods

2.1 Site description and sampling

As shown in Fig. 1, the altitude of the research location in Kohgiluyeh and Boyer Ahmad Province located in the southwest of Iran ranged from 500 m in lowlands to 4409 m above sea level, with an expansion of geographic coordinates from $30^\circ 33'$ to $30^\circ 38'$ N latitude and from $51^\circ 47'$ to $51^\circ 50'$ E longitude. This research was undertaken in the Kakan plain (located about 20 km east of Kohgiluyeh and Boyer Ahmad Province) with “Xeric” and “Mesic,” soil moisture, and temperature regimes, respectively. For the intention of this examination, with the backing of preceding soil investigation (Shakeri, 2015) and using satellite images and topographic and geological maps of the study area, five different land-use systems including wheat, garden, forest, rangeland, and fallow fields selected in the Kakan plain were examined (samples were taken from the same physiographic units). To

Fig. 1 Location of Kohgiluyeh and Boyer-Ahmad Province, southwestern Iran



assess the distribution of assorted forms and unhariness of K fixation, three pedons for every land use and usually 15 pedons were selected, described, and arranged by the Soil Survey employees in 2014 (US Soil Taxonomy System). Sampling soils were categorized as Typic Calcixerepts, Typic Haploxerepts, Calcic Haploxeralfs, and Aquic Haploxeralfs (Shakeri, 2015). From different soil horizons, surface layers (0–30 cm depth) and subsurface layers (30–60 cm depth) were sampled. The samples were then dried within the laboratory in the presence of air and were then aged with a sieve of two linear metric units. Based on the physical, chemical, biological, and environmental factors touching K kind and K balance in soil, which can be associated with clay geology, several experiments were performed. In this context, various soil properties were assessed using specific methods: Texture analysis employed the hydrometer method (Scavo et al., 2019), Cation Exchange Capacity (CEC) was determined by cation replacement with sodium acetate (Gruba & Mulder, 2015), Soil pH was measured through 1:1 water-to-soil extraction (Auge et al., 2017; Lalitha & Dhakshinamoorthy, 2014; Wiyantoko & Rahmah, 2017), Calcium Carbonate Equivalent (CCE) was calculated using volumetric measurements via calcimetry (Akrawi, 2018), and Soil Organic Carbon (SOC) content was assessed using the wet oxidation method (Bhunia et al., 2018; Zhao et al., 2014).

2.2 Data collection and analysis

2.2.1 Mineralogical analysis

For the preparation of specimens for the identification of clay minerals (Kenny, 2021), the elimination technique of cementitious chemical substances and the segregation of clay particles from one another became the fundamental approach. For this purpose, data were collected from a long period of time that accurately reflects land-use change. First, at 80 °C, soil carbonates are removed in a bath using a normal solution of sodium acetate (pH=5). To remove organic matter, 30% H₂O₂ was used. Mn dioxide is also removed during this step. Then, Fe oxides were extracted by using citrate dithionate. After the cementitious materials including lime, organic matter, and oxides have been removed, the sand and silt

particles must be deposited by centrifugation. Under these conditions (750 rpm for 5 min and 30 s), the clay remains as a suspension in the centrifuge tube. This suspension is poured into a cylinder so that the clay particles are air dried and prepared for various treatments and identification after settling the clay particles and siphoning the water. This is a well-known method used to separate clay particles, and, as mentioned, with this method and with this centrifuge, the clay is not sedimented by centrifuge but by silt and sand particles sediment. After clay separation (750 rpm for 5 min and 30 s), for clay mineralogy, the following samples of fine and coarse clays were analyzed for X-ray diffraction analysis of saturated Mg and K with three washes, respectively. They are deionized with 0.5 MgO₂ and one M KCl, followed by successive washings with H₂O. The samples were X-rayed once air drying, and once heating at 550 °C for 2 h. Samples soaked with Mg were examined after drying in open air and after being exposed to the unobstructed surface of ethylene glycol at a temperature of 60 °C for a duration of 2 h. For clay mineralogy, fine and coarse clay subsets were analyzed for X-ray diffraction analysis of saturated Mg and K by triple washing with 0.5 MgO₂ and 1 M KCl, respectively, followed by successive deionization with H₂O. After drying, the glycerol solution samples were heated at 60 °C for 3–6 h to evaporate the excess glycerol (Furquim et al., 2010; Ransom et al., 1988).

The percentage of clay minerals could be calculated semi-quantitatively based on a tactic recommended by Kenny (2021), Relative peak areas in heat loss in glycerol treatment.

2.2.2 Different forms of K

Interchangeable K with a nominal utilization of twenty-five metric capacities per unit weight of NH₄OAc unit weight at hydrogen ion concentration was 7.0, stirred at 25 °C for 60 min and filtered before decomposition (Baliuk et al., 2015; Meyer et al., 2018). The non-exchangeable K was derived by adding 25 mm of one MHNO₃ to a pair of 0.5 g of soil and boiling it for 15 min (Murrell et al., 2021; Sparks et al., 2020). Total K is dissolved in a mixture of HF-HClO₄ and HNO₃ by separating soil samples (ground for passing through a 0.17 mm sieve) (Murrell et al., 2021; Rogiers et al., 2017; Shetaya et al., 2019).

2.2.3 Potassium release and fixation experiments

After performing physico-chemical tests and estimating various K forms, samples were selected to conduct non-exchangeable K (NEK) kinetics release. First, exchangeable K was removed through saturation by leveling 10 g of soil with one M of CaCl₂ for forty-eight h thrice. The extra CaCl₂ was then washed out of soil by suspension with alcohol and deionized water, followed by centrifugation. Samples were dried and ground to resolve the agglomeration in an oven at 65 °C. In the next step, 20 mL of the solution of calcium chloride (0.01 M) was added to a centrifuge tube containing Ca-saturated soil (2 g). Similarly, in another centrifuge tube, two g of soil and 20 cc of the answer of ethanedioic acid (0.01 M) were another, severally. The duration of different areas in each type of management has been about 40 years. The extraction pairs, as prepared for different samples, were stirred on a shaker for 15 min at 25 °C. Then, they were centrifuged, and the supernatant solution was stored for subsequent determination. The remaining soil in the tube was re-extracted a further 14 times, and the released K in each of the 15 stages for K + concentration, flame photometer (Elico Model CL-360) was calculated (Meyer et al., 2018). Then, the released non-exchangeable K was fitted with different kinetic equations versus time. These equations are as follows:

$$\begin{aligned}
 \text{Parabolic diffusions : } K_t &= a + bt^{1/2} \\
 \text{Power function: } \ln K_t &= \ln a + b \ln t \\
 \text{Simplified Elovich : } K_t &= a + b \ln t \\
 \text{First order : } \ln (K_0 - K_t) &= a - bt \\
 \text{Zero order : } (K_0 - K_t) &= a - bt
 \end{aligned}
 \tag{1}$$

K_0 is the volume (mg/kg) of total K , released within the time t (h); K_t is the maximum released cumulative K , and the constants of the equations are (mg/kg) a and b . The equations were compared based on determination coefficients (R^2) and normal calculation errors (SE). The standard errors of estimation were calculated using the following equation:

$$SE = [(K - K^*)^2 / (n - 2)]^{1/2} \tag{2}$$

In this formula, K and K^* symbolize the amount of computed and predicted non-interchangeable K , while n indicates the quantity of the assessed information. To measure the amount of K fixation, five g of soil samples were poured into centrifuge tubes, and after adding four levels of K (150, 300, 600, and 1000 mg/kg soil), the samples were shaken for 24 consecutive hours. Then, they were dried for 24 h at 50 °C. This process was repeated three times.

Other samples were treated in the same way, but instead of being placed in the oven and drying, they were equilibrated at room temperature. Then, the samples were extracted by one M NH_4OAc three times, and the resulting extracts were stored for K measurement by flame. The quantity of K fixation was computed using the following formula:

$$K_{\text{fixed}} = K_F + K_{\text{ec}} - K_{\text{et}} \tag{3}$$

where K_F : added K ; K_{ec} : native K ; K_{et} : K extracted by NH_4OAc .

3 Results and discussion

3.1 Characteristics of soil, mineralogy, and K forms

Table 1 presents the results of some soil characteristics in various land uses. The median pH of the soil uses under study was 7.4, ranging from 6.5 to 7.7, with the highest and lowest values for the wheat and garden land uses, respectively. Because of the rise in soil organic matter (SOM) in the use of land in the garden and the use of various fertilizers by farmers, the soil pH in the garden land use decreased compared to other land uses, which aligns with the results of Malo et al. (2005). Boostani et al. (2019), by comparing a number of soil properties in different land uses, reported that cation exchange capacity, organic matter, and pH in forest and pasture land uses have been significantly more than those in the orchard land use. However, the organic carbon changes in the study soils range from 0.9 to 1.94% and are related to fallow and forest uses, which is due to differences in mineral structures in different soils. This is because in the soils under cultivation and fallow, the soil disturbance through the changes in the soil temperature, moisture, and aeration increases the rate of organic matter decomposition. Khormali and Kehl (2011) reported that the forest and pasture lands add more organic matter (OM) to the soil due to the short and often annual grass cover. The changes in soil texture in the land uses under study were

Table 1 Mean varieties of K, accumulative non-exchangeable K (NEK) discharged by 0.01 M CaCl₂ (mg/kg), ethanedioic acid, and a few soil properties

| Pedon | Soil orders | Land use | Soluble K | Exchangeable K (surface-adsorbed K) | Non-exchangeable K | Structural k | Rel* (Cacl ²) | Rel* (Oxalic) | Clay (%) | Sand (%) | pH | CCE (%) | OC (%) | CEC (cmol (+) kg ⁻¹) |
|-------|-------------|----------|-----------|-------------------------------------|--------------------|--------------|---------------------------|---------------|----------|----------|------|---------|--------|----------------------------------|
| 1 | Alfisols | Pasture | 3.55 | 216 | 288.5 | 2301 | 217 | 203 | 49.7 | 15.85 | 7.35 | 50 | 1.14 | 32.5 |
| 2 | Alfisols | Garden | 2.7 | 404 | 523 | 3118 | 288 | 286 | 52.7 | 16.6 | 6.5 | 24 | 1.26 | 39 |
| 3 | Mollisols | Fallow | 3.3 | 122.0 | 224.3 | 2676.0 | 144.0 | 145.0 | 31.6 | 23.9 | 7.5 | 50.0 | 0.9 | 23.0 |
| 4 | Inceptisols | Wheat | 9.1 | 155 | 438 | 4641 | 170 | 176 | 36 | 21 | 7.7 | 36 | 1.05 | 18 |
| 5 | Inceptisols | Forest | 3.7 | 325 | 488 | 4244 | 295 | 274 | 46 | 17 | 7.6 | 65 | 1.94 | 39 |
| Mean | - | - | 4 | 210 | 337 | 3079 | 202 | 197 | 41.1 | 19.8 | 7.4 | 47 | 1.2 | 28.8 |
| Max | - | - | 9.1 | 404 | 523 | 4641 | 295 | 286 | 52.7 | 23.9 | 7.7 | 65 | 1.94 | 39 |
| Min | - | - | 2.7 | 122 | 224.3 | 2301 | 144 | 145 | 31.6 | 15.85 | 6.5 | 24 | 0.9 | 18 |

Rel*: cumulative non-exchangeable K (NEK) discharged by zero.01 M CaCl₂ and ethanedioic acid

in a way that the texture of pasture, forest, and garden land use was clay, the texture of fallow land use was loamy clay, and, finally, the texture of wheat land use was loamy clay. The studied soils were calcareous, with an average CCE of 47%, which was observed in the range of 24–65% in the garden and forest land uses, respectively. Since the land uses under study had a relatively identical amount of parent material, the change in the amount of equivalent calcium carbonate can be related to the change in land use. The average CEC was 28.8 cmol (+). kg⁻¹, and the lowest amount was observed in the areas related to wheat land use. It appears that the continuous and extended farming of wheat has diminished the CEC of wheat farmland in comparison to other land uses. As mentioned in the materials and methods section, “in laboratory research, different soil horizons, as well as surface layers (depth 0–30 cm) and subsurface layers (depth 30–60 cm), were sampled and air-dried, and the field was used to move in a 2 mm sieve.” Due to the fact that the depths of the horizons were different in different profiles for uniformity of work, after describing and interpreting the horizons, as well as classifying the soils of the region, we used these two surface and depth horizons (depths of 0–30 and 30–60 cm). Separate sampling and all experiments in addition to the specified horizons were performed at these two depths, and the average obtained from the results of these two horizons is given in Table 1.

Table 2 shows the relative abundance of clay minerals within the soils of the study area. As can be seen, the types of minerals in different land uses are similar and differ only in the amount of the proportions in different land uses, depending on the type of land use and the management applied. Smectite is also the most significant and plentiful mineral present in the region's soils. The study area has high rainfall, and the conditions seem to be adequate for the changes in primary minerals and their conversion to minerals such as smectite. The soil profiles situated in the lowlands of the area possess a smooth consistency and inadequate water drainage circumstances. Therefore, the neoformation source according to the drainage conditions and also the high pH and high activity of silica ions in these conditions can be considered one of the most important causes of the abundant smectite in these pedons. Another factor that can be linked to the elevated concentration of the mineral in the low-lying regions of the area is the transformation of palygorskite into smectite, which occurs in regions with abundant precipitation. No palygorskite mineral was detected in any of the soil profiles within this vicinity.

Table 2 Numerical findings of clay minerals in certain layers within the examined land utilization

| Pedon | Land use | Depth (cm) | Quartz | Vermiculite | Smectite | Chlorite | Illite | Kaolinite |
|-------|----------|------------|--------|-------------|----------|----------|--------|-----------|
| 1 | Pasture | 30–0 | + | + | + | +++ | ++ | + |
| | | 60–30 | + | + | + | ++++ | ++ | + |
| 2 | Garden | 30–0 | + | + | +++ | ++ | + | + |
| | | 60–30 | + | – | + | ++ | ++ | ++ |
| 3 | Fallow | 30–0 | + | + | +++ | ++ | + | + |
| | | 60–30 | + | + | +++ | ++ | + | – |
| 4 | Wheat | 0–30 | + | – | ++++ | +++ | + | + |
| | | 30–60 | + | – | +++ | ++ | + | + |
| 5 | Forest | 0–30 | + | – | +++ | +++ | + | + |
| | | 30–60 | + | – | +++ | ++ | ++ | + |

+++ , content in the range of 30–50%; ++ , content in the range of 15–30%; + , content < 15%; – , trace or not detected

In the study of calcareous soils, Shakeri and Abtahi (2020) attributed the high smectite in the soils with low to moderate rainfall to the parent materials and rock and in the areas with higher rainfall to the neof ormation and degradation of other minerals and the conversion of palygorskite to montmorillonite. In almost all pedons studied, the amount of smectite increased from surface to depth. The reason for the higher amount of this mineral in depth can be attributed to the transfer of this mineral from the surface to the depth due to the humid climate of the region. At the soil level, the conditions are provided for converting other minerals such as palygorskite and illite to smectite, but the rainfall in the area and the fine size of this mineral lead to the transfer to the lower parts of the pedon. The amount of vermiculite mineral in the soils of the region is less than 5%, and there is no significant difference in the amount of this mineral between surface and deep horizons.

As noted in the materials and methods section, K-saturated samples are heated: “For clay mineralogy, sub-samples of fine and coarse magnesium and potassium clays for X-ray diffraction analysis were saturated with three washes with 0.5 ml MgO_2 and 0 M KCl, and after successive washing with deionized H_2O and air drying. Samples were taken by X-ray after heating at 550 °C for 2 h.”

The reason for the low vermiculite content in the soils of the region can be attributed to their instability in high magnesium, and the soils' alkaline pH conditions contribute to the instability of this mineral in the conditions of mica formation causing this mineral to quickly turn into smectite (Khormali & Abtahi, 2003). Unlike many soils with significant concentrations of illite in southern Iran, the amount of this mineral in the region is very low because of the conversion of this mineral to smectite due to the weathering process, and, as a result, K is released and converted to smectite. Excessive leaching facilitates the release of K from mica and causes the weathering into 2:1 minerals (Shahrokh et al., 2023). The mineral illite exhibited a decline in forest and garden land uses as depth increased, primarily because of the enhanced influx of illite from the neighboring regions. This decrease in illite can be attributed to its origination and transfer through erosion and wind to the surface soils, as well as the transformation of biotite in surface soils caused by fluctuations in moisture and temperature on a daily and seasonal basis (Shakeri & Abtahi, 2020). Transformation of illite to smectite occurred primarily in surface soils that had high levels of organic matter, as well as in other soils found in humid regions. Due to its presence in the fine fraction, smectite was able to migrate and settle in the subsurface horizon, unlike illite. Chlorite, on the other hand, exhibited independent behavior in relation to soil depth, land use, and climate. Both illite and chlorite are inherited in nature. Kaolinite was found in tropical conditions, and its presence in the study area was inherited from the surrounding formations and sediments.

3.2 K forms in different land uses

Table 1 and Fig. 2 display the measurements of different soil potassium types under the impact of different land practices. Soluble K could be a sort of K that may be quickly used for plant and soil microorganisms. The soluble K level of the soil is low and depends on the depletion (absorption by the plant or leaching) and replacement of the exchangeable types (E-K) (surface-adsorbed K) and non-exchangeable (NE-K) soil. The quantity of soluble potassium (SOL-K) in the examined soils ranged from 2.7 to 9.1 mg/kg (average: 4 mg/kg). In soil, soluble K is readily leached and readily available to plants. The amount of K solution depends on the balance between the various sorts of K within the soil and therefore the use or removal of K from the soil. The balance between soluble and exchangeable

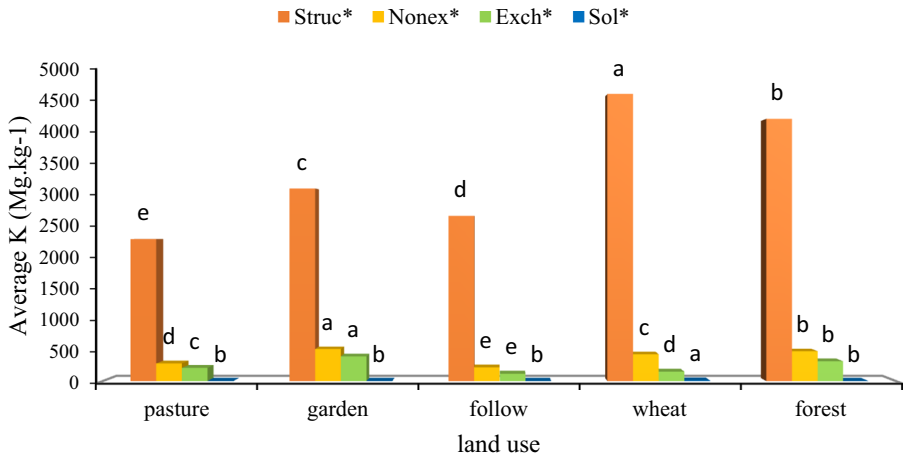


Fig. 2 Comparison of average values of K forms in various land uses (a, b, c, d averages denoted by distinct letters are significantly distinct at $P < 0.05$.) *(struc: structural; Nonex: non-exchangeable; Exch: exchangeable surface-adsorbed K, and Sol: soluble K)

potassium depends on the properties of the soil, such as pH, CEC, and the geology of the clay, and may be fraught with weathering of ions in the separable soil resulting in the total concentration of soluble anions. The results obtained within the sample space, considering distinct land uses, recommended that the best quantity of soluble K was determined within the wheat land use, which was considerably more than different land uses; however, among different land uses in terms of soluble K, no important distinction was determined. One of the reasons for this higher amount is the way K fertilizers are managed and used. The minimum quantity of this type of K was noticed in the garden land utilization. K concentration in agricultural soils may be partly related to intensive management changes such as crop rotation, irrigation, land reclamation, and fertilizer management. Nonetheless, Samadi et al. (2008) and Taghipour et al. (2015) reported a notable decrease in K as a result of prolonged agricultural practices and farming. Exchangeable K (EK) is a form of K stored by the negative charges of organic and mineral colloids (Ghiri et al., 2011; Hosseinpur & Kalbasi, 2001).

K absorbed on organic matter or clay minerals is the same as EK, which is easily exchangeable with other cations. A relatively small portion of the overall K within the soil is surface-adsorbed K and varies from one hundred to over 2000 mg kg⁻¹ in the soil (Das et al., 2022). As depicted in Fig. 2, the EK diagram illustrates that there are notable variations in EK across various land uses, as the fallow land use had the least amount of EK and the garden land use had the most amount. The low level of this form of K may be associated with the lower clay levels in the fallow land use rather than other ones. Nabiollahy et al. (2006) attributed the difference in the amount of EK in different soils to the different amounts of clay in the soils. Jafari and Baghernejad (2007), in a study on the soils in Khuzestan region, showed that EK exists only in the clay part of the soil, and other components play a small role. The main causes for the significant quantity of (surface-adsorbed K) K (EK) in the garden land use may be the fact that EK is stored by electrostatic bonding on clay and organic matter, and in the garden land use, the amount of organic matter is relatively high and there is a higher amount of clay and CEC compared with other uses. Therefore, the significant quantity of this type of K in the land utilization is not surprising.

In addition, according to the results, the soil EK had a positive and significant association with the amount of soil CEC, and such results were reported by Azadi et al. (2016) in calcareous soils. As such, in the study area, the parameters of CEC and calcium carbonate have a significant relationship, and clay, organic carbon, illite, smectite, and vermiculite have a direct relationship with EK, as presented in Tables 3 and 4 (0.574*, -0.668**, 0.092, 0.241, 0.721, 0.765, and 0.193, respectively).

A small amount of total soil potassium is NEK, EK, and type of separation, and the rest of this part is irreplaceable and structurally inside the soil. Although the non-exchangeable kind is not without delay obtainable to the plant, it has been determined that by extracting the grain, the quantity of this manner of K within the soil is ablated (Srinvasa Rao et al., 2000). In the examination of soil NEK, the findings demonstrated that there is a noteworthy distinction between various land practices (Fig. 2), as there is the minimum quantity of NEK in the uncultivated land practice, followed by the grazing land practice which may be attributed to the lack of addition of K fertilizers to the fallow and pasture soil, lack of soil disturbance, and lack of mineral weathering. The minimal erosion of clay minerals and reduced levels of CEC in the soils of this land use have resulted in a decline in potassium (K) in both the exchangeable and non-exchangeable forms. Moreover, the impoverished territories beneath the unused land utilization, the grazing land utilization in the area, the absence of flora, and diminished organic material have resulted in a decrease in the breakdown of minerals and, consequently, a decline in the liberation of potassium from minerals. The NEK has a crucial connection with CEC (0.694**) and carbonate (-0.712**) and a favorable connection with clay (0.182), smectite (0.752), illite (0.744), and vermiculite (0.258). The strong correlation between the amounts of clay and K underscores the significance of the clay composition in terms of the quantity of this type of K. The negative correlation of calcium carbonate with the released NEK is due to the dilution effect. The highest amount of NEK in the garden land use, which is also related to Alfisol soil, could be due to more clay smectite with separate layer charges and the presence of the K source of illite and vermiculite. These findings align with the findings of Shakeri and Abtahi (2018) who concluded that soils containing smectite have a higher mineral NEK higher than chlorite and soils containing palygorskite as the predominant minerals. Hosseinpur et al. (2014) stated that heavy textured soils (clayey) and prevalent smectite soil minerals have a higher amount of NEK. Mineral K, also known as structural K, may account for up to 98% of soil K, and the composition of the parent rock depends on the stage of soil development (Sparks, 2000). The findings indicated that there was a significant disparity in the structural K between the studied land uses, as the highest and lowest amounts of structural K are related to the wheat and pasture land uses, respectively. The structural K had a significant relationship with NEK and CEC and showed a direct and positive relationship with clay minerals. Furthermore, it showed a direct and negative relationship with calcium carbonate and gravel. These findings suggest that smectite, with a high layer charge, vermiculite, and illite, has a notable impact on the quantity of potassium minerals in the examined soils (Shakeri & Abtahi, 2018). The negative relationship of this form of K with the amount of calcium carbonate and its positive relationship with the amount of clay show that lowering the calcium carbonate increases the actual amount of clay in the soils with less calcium carbonate and, thus, increases the relative amount of the minerals. As a result, in the soils with more clay and less calcium carbonate, there are more structural and other forms of K.

To investigate a factor affecting soil properties, the conditions under which those soils must be formed must be the same. Given that the samples were taken in an area with the same climatic conditions and parent materials, another important factor that requires the same conditions is the same effect of topography on soil formation. Therefore, soils were

Table 3 Correlation factors (Pearson) for linear connections between various K forms and certain physico-chemical characteristics of soils in the examined region

| | Soluble K | Exchangeable K (surface-adsorbed K) | Non-exchangeable K | Structural K | CCE | CEC | OC | Clay |
|--------------------|-----------|--|--------------------|--------------|---------|---------|--------|----------|
| Exchangeable K | 0.487 | | | | | | | |
| Non-exchangeable K | 0.640* | 0.948** | | | | | | |
| Structural K | 0.528 | 0.466 | 0.678** | | | | | |
| CCE | -0.576* | -0.668** | -0.712** | -0.510 | | | | |
| CEC | 0.611* | 0.574* | 0.694** | 0.838** | -0.644* | | | |
| OC | -0.054 | 0.241 | 0.078 | -0.343 | -0.009 | 0.395 | | |
| Clay | 0.107 | 0.092 | 0.182 | 0.353 | -0.006 | 0.602* | -0.368 | |
| Sand | -0.054 | -0.022 | -0.091 | -0.470 | -0.076 | -0.598* | 0.526 | -0.767** |

* and ** represent significance levels of 0.05 and 0.01, respectively

Table 4 Correlation coefficients (Pearson) for liner connections between potassium forms in the soil and clay minerals in the investigated regions

| | Soluble K | Exchangeable K (surface-adsorbed K) | Non- exchange- able K | Structural K | Illite | Vermiculite |
|--------------------|-----------|---|-----------------------------|--------------|--------|-------------|
| Exchangeable K | 0.643 | | | | | |
| Non-exchangeable K | 0.659 | 0.997** | | | | |
| Structural K | 0.248 | 0.661 | 0.686 | | | |
| Illite | 0.878* | 0.721 | 0.744 | 0.647 | | |
| Vermiculite | 0.099 | 0.193 | 0.285 | 0.355 | 0.136 | |
| Smectite | -0.895* | 0.765 | 0.752 | 0.136 | -0.707 | 0.095 |

* and ** represent 0.05 and 0.01 levels of significance, respectively

selected from the same physiographic units and different land uses. In the materials and methods section, the sentence “samples were taken from the same physiographs” was added to the text.

3.3 K release

The sequential extraction of NEK was performed with 0.01 M calcium chloride and 0.01 M oxalic acid in 15 steps and two replications for different land uses. The cumulative K was released over time with both extractants in different land uses in the region (Fig. 3). This shows that in all land uses with both extractants, the mechanism of K release is approximately the same, except the rate of release that is initially high and decreases over time. According to Mondéjar-Parreño et al.’s (2021) findings, there is no reliable extraction method for the separation of different forms of K; it is not possible to say with certainty that one method of extraction can release only non-exchangeable K or that another method can only release exchangeable K. Therefore, the topics of this section are relative, and based on the authors’ knowledge, the methods of extracting 0.01 M calcium chloride and 0.01 M K oxalic acid are considered irreplaceable. However, some other forms of K may also be released this way. In the early stages, as the NEK is situated at the edges and between the layers, the K at the edges of the minerals that are more accessible is first released. Over time, the K in the wedge-shaped sections, which is more difficult to extract, is released. The Ca^{2+} ions cannot be rapidly positioned between the mineral layers and released K because the hydrated radius is larger than K^{+} , the potassium’s distance from the edges increases over time, and the release rate decreases. Consequently, the presence of K at the edges is linked to the initial half of the cumulative release curve, while K in the wedge and interlayer is associated with the latter part (Benipal et al., 2006).

Azadi et al. (2015) and Shakeri and Abtahi (2018) examined the release of potassium from the soil and showed that the release of potassium was rapid in the beginning. However, the number of Ks generated in the first part of the curve was an honest prediction of the number of Ks in the plants in the next value. It was also stated that the K release follows the diffusion process. The results are presented in detail in Table 1. Regarding the release rate of the two extractants, according to the results presented in Table 1 and Fig. 4, there is a considerable difference between the K extracted by calcium chloride and oxalic acid in different land uses. The highest NEK was released with both extractants

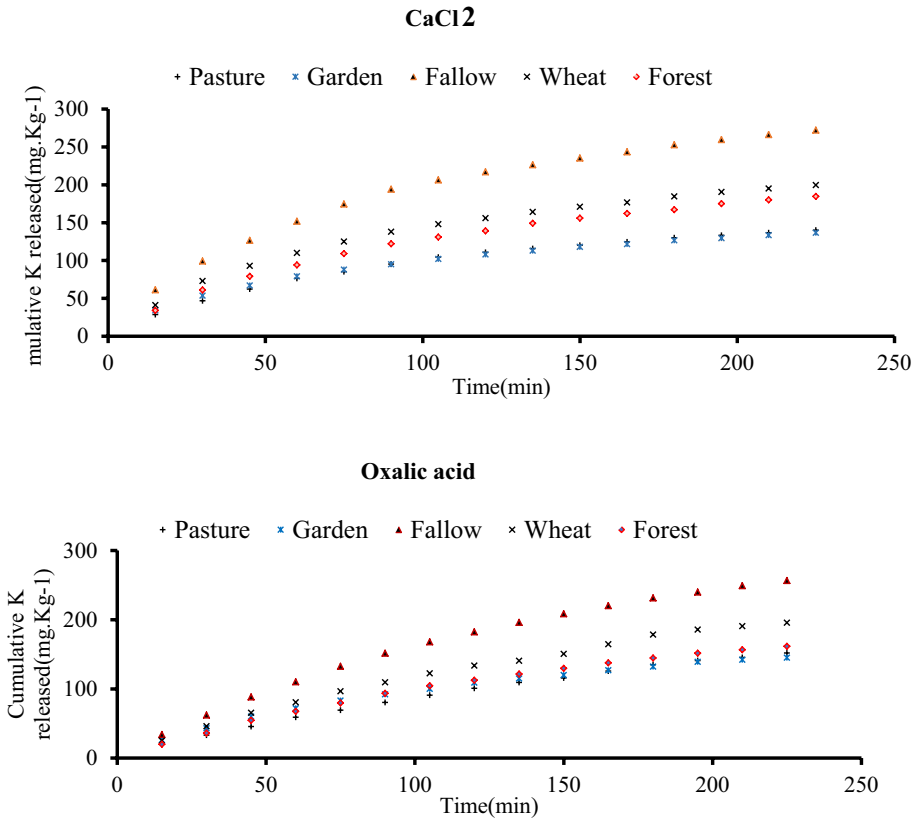


Fig. 3 Cumulative K released to 0.01M CaCl₂ and Oxalic acid with time in various land uses

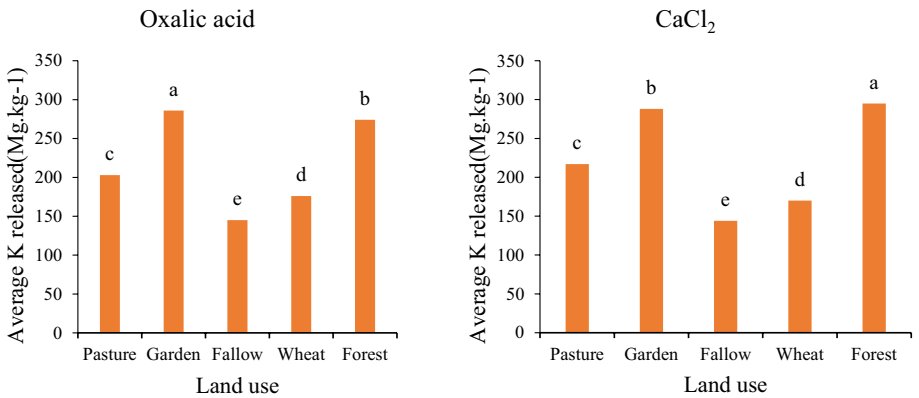


Fig. 4 Mean values with multiple superscripts are significantly distinct ($P < 0.05$) in terms of the amount of K released by CaCl₂ and Oxalic acid extractants in various land uses

in the forest and garden land uses with calcium chloride and oxalic acid extractants. The land uses (i.e., forest and garden) had the highest release rate because they contain soils with high NEK, CEC, clay content (especially smectite), and organic matter. The lowest unharness rate in each extractant of salt and acid was a hundred and forty-four and a hundred forty-five mg kg^{-1} and was associated with the utilization of fallow ground, severally. The fallow land use contains the lowest amount of NEK, organic matter, and clay content among the land uses under study. This is attributed to the lack of addition of K fertilizers, lack of soil disturbance, and lack of mineral weathering. The less weathering of clay minerals and lower CEC level in the soils of fallow land use led to the decrease in the NEK level. Moreover, the impoverished areas beneath the uncultivated terrain are experiencing a decrease in vegetation, leading to a decrease in the breakdown of minerals and, consequently, a decline in the liberation of potassium from minerals. NEK had a favorable connection with CEC and organic substances in the research regions. Soil organic substance can be seen as an abundant origin of ions. Moreover, the decomposition of organic substances in the soil is a vital factor in the creation of organic acids in the soil, which triggers the erosion of clay minerals (a primary origin of NEK) and the liberation of NEK, thereby escalating the quantity of K that can be assimilated. Shakeri (2015) reported that although the amount of illite was the same in almost all pedons, the minerals associated with illite play an important role in the amount of NEK release, and due to the humidity of the area, the minerals associated with illite, including vermiculite, high layer charge smectite, and mixtures of illite–smectite, have a vital role in the release of NEK in various land applications in the area. Shakeri (2015) stated that the release of NEK from minerals and, as a result, the increased concentration of soluble and exchangeable K increased with increasing the organic matter, indicating the importance of organic matters in the diffusion of various sources of K in the soil.

Typically, in every calcium chloride specimen, the average quantity of K removed was 202 mg/kg, ranging from 144 to 295 mg/kg, and the discrepancy in the quantity of K generated by consecutive oxalic acid extraction was 197 mg/kg, ranging from 145 to 286 mg/kg. The amount of NEK released by oxalic acid in almost all samples was less than the NEK released by calcium chloride, which is mainly due to the high buffer capacity of calcareous soils and the neutralization of oxalic acid with calcium carbonate.

Jalali and Kolahchi (2007) extracted, on average, about 340 mg/kg of NEK from calcareous soils of Hamedan province in western Iran. The liberation of NEK is not inherently the outcome of the disintegration of K-containing minerals; nevertheless, it is also a gradually evolving response. The K-substituted ion in the anhydrous form can first join the non-expanded interlayers when there is a sluggish exchange between clay minerals such as illite, and, then, the interlayers should be simultaneously expanded with the hydration of the expanded ions. This particle is allowed to bind or lure, and also the release of hydrous K unceasingly propagates to exchange sites within the outer part of the clay particles (Sparks & Huang, 1985).

To investigate the NEK release rate of soils in the land uses studied in the region with two extractants of 0.01M calcium chloride and 0.01M oxalic acid, the data of the NEK release stages was fitted with the first-order Elovich. Table 5 exhibits the curved diffusion, exponential function equations, and equation parameters. The determination coefficient and the normal mistake were used to determine the best equation. As can be seen, there is a close coefficient for the exponent function, quadratic spreading, and Elovich formulas for the 0.01 M calcium chloride extractant of determination, but the lowest standard error is related to the power function equation. For the 0.01 M oxalic acid extractant, Elovich, power function, and parabolic diffusion equations have the highest coefficient

Table 5 The determination constant (R²), normal error of estimates (SE), and a and b constants describing non-exchangeable K dynamics for soil

| Land use | Elovich | | | First order | | | Parabolic | | | Power function | | | |
|----------------------------------|---------|------|-------|-------------|-------|----------------|-----------|------|----------------|----------------|------|----------------|------|
| | a | b | SE | a | b | R ² | A | b | R ² | a | b | R ² | SE |
| <i>Oxalic acid (0.01 M)</i> | | | | | | | | | | | | | |
| Pasture | -181 | 69 | 10.4 | 5.7 | -0.02 | 0.92 | -35 | 16 | 0.99 | 1.5 | 0.72 | 0.99 | 0.05 |
| Garden | -249 | 96 | 12.5 | 6.0 | -0.01 | 0.94 | -43 | 22 | 0.99 | 4 | 0.70 | 0.99 | 0.06 |
| Fallow | -129 | 49 | 8.1 | 21.8 | -0.02 | 0.92 | -25 | 11 | 0.99 | 2.5 | 0.71 | 0.99 | 0.04 |
| Wheat | -169 | 61 | 12.1 | 5.5 | -0.01 | 0.93 | -41 | 14 | 0.99 | 2.9 | 0.77 | 0.99 | 0.03 |
| Forest | -281 | 99 | 18.5 | 6.1 | -0.02 | 0.92 | -71 | 23 | 0.99 | 4.8 | 0.83 | 0.99 | 0.05 |
| Average | -202 | 75 | 12.31 | 9.0 | -0.02 | 0.92 | -43 | 17 | 0.99 | 3.5 | 0.75 | 0.99 | 0.05 |
| <i>CaCl₂ (0.01 M)</i> | | | | | | | | | | | | | |
| Pasture | -130 | 63.5 | 4.1 | 5.5 | -0.02 | 0.96 | 7.5 | 14.5 | 0.99 | 6.5 | 0.52 | 0.98 | 0.06 |
| Garden | -158 | 82 | 5 | 5.8 | -0.02 | 0.95 | 21 | 19 | 0.98 | 9.3 | 0.48 | 0.98 | 0.05 |
| Fallow | -98 | 44 | 3.9 | 5.1 | -0.02 | 0.95 | -3 | 10 | 0.99 | 3.5 | 0.56 | 0.99 | 0.05 |
| Wheat | -118 | 53 | 4.3 | 5.3 | -0.02 | 0.96 | -4 | 12 | 0.98 | 5.5 | 0.57 | 0.98 | 0.06 |
| Forest | -239 | 98 | 9 | 5.9 | -0.02 | 0.96 | -26 | 22 | 0.98 | 10.5 | 0.66 | 0.98 | 0.08 |
| Average | -149 | 68 | 5.3 | 5.5 | -0.02 | 0.96 | -0.9 | 15.5 | 0.98 | 7.0 | 0.56 | 0.98 | 0.06 |

of determination. The power function equation for calcium chloride and oxalic acid has a coefficient of determination, with an average of 0.99 and 0.98 and a standard error with an average of 0.05 and 0.06, respectively. Due to the small standard error and large determination coefficient for both extractants, this equation is known as the best equation for the soils of the region in different land uses.

Sharma and Sharma (2011) concluded that with the slow release of potassium from the bedrock positions of mycotic minerals, the ability to perform the equation is often required to prove the dominant velocity of the potassium opening mechanism. The parabolic diffusion and Elovich equations were defined as the better equations followed by the power function equations due to the high coefficient determination for calcium chloride and oxalic acid extractants. Jalali and Khanlari (2014) examined the kinetics of NEK release in different land uses in calcareous soil and stated that the most suitable equations for the release of combined K in all land uses are, in general, the equations of parabolic distribution, Elovich, and power functions. Jalali and Zarabi (2006) proposed the power function equation for the two extractants of calcium chloride and oxalic acid. In a study of calcareous soils in southwestern Iran, Shakeri and Abtahi (2018) and Azadi et al. (2015) proposed Elovich equations for power performance and first order and parabolic diffusion because they are best used to predict NEK release of studied soil separately. They also stated that the coefficient of release rate (b) in the Elovich and parabolic diffusion equations showed a significant correlation with NEK and a number of soil's physico-chemical properties. The slope of equation (b) indicates the release rate of the interlayer K, which had the highest value in the forest and garden land uses. Among the equations, the Elovich equation had the highest amount of K release rate with the two extractants. As can be seen, the fallow land use, which has the lowest release coefficient, has the lowest levels of clay, CEC, and organic carbon, while the soil of forest and garden land uses have the highest levels of clay, CEC, and organic carbon.

3.4 K fixation

The effects of the wetting and drying of fixed K content and normal treatments on the surface and subsurface soils of different land uses are presented in Table 5. As can be seen, the lowest and highest levels of K fixation in the surface and subsurface horizons in the normal treatment were observed in the garden (285 mg/kg) and forest (114 mg/kg) land uses, respectively, and in the wet and dry treatment, the garden (395 mg/kg) and forest (278 mg/kg) land uses had the highest and lowest fixation values, respectively. The mean fixation rate of the samples in the normal treatment in the surface and subsurface soils of all land uses was 136 and 114 mg/kg, respectively, and in the wet and dry treatment was 323 and 278 mg/kg, respectively. The soils of the region have very little illite, and smectite is the predominant mineral of the region. The presence of smectite with a high layer charge caused the soils to contain more smectite to absorb more K between their layers. The highest fixation rate, both in the normal and wet and dry treatments, occurs in the subsurface soil of garden land use because it is related to the subsurface horizons of Alfisol which have more smectite than the surface horizons. Smectites are 2:1 clay expandable that expands up to 17° in ethylene glycol treatment. High-layer smectites, however, have less expansion and may expand to about 15–16 °C. Due to this feature, smectite with a high layer charge can also be identified. Many factors affect the fixation of potassium as well as soil quality and soil frequency, wet and dry, freezing and thawing, soil pH, use of potassium fertilizers, soil moisture content, and potassium concentration relative to different cations such as metal

and atomic number 12 (Brady et al., 2008; Sparks, 2000). The lowest rate of fixation in wet, dry, and normal treatments is relevant to forest land use, which occurred despite the presence of high amounts of clay, CEC, and organic matter. This is because organic matter can reduce the rate of K fixation by entering the interlayer sites and expansion of layers, increasing soil CEC, and increasing the production of organic acids, resulting in the dissolution of minerals and their release of K. In general, it can be stated that the K fixation in the surface and subsurface soils does not follow a specific trend because in some soils such as land uses 1, 2, 3, and 4, the K fixation in the normal treatment in the surface horizons is less than that of the subsurface soils; however, in land use 5, i.e., forest land use, the fixation rate is higher than that of the subsurface soil. The fixation rate in top soils is higher than that of subsurface soils in wet and dry treatments for fallow and woodland land uses. In general, the average rate of K fixation in both treatments in surface soil is less than that of subsoil in both soil applications (Table 6).

Land use change from forest to agriculture in different regions, especially in arid and semi-arid regions, leads to changes in the amount of organic matter, and organic matter has an important role in soil properties, including the effect of release or fixation of elements. As a result, land use change can play an important role in increasing or decreasing K fixation. The distribution of layered charges was explained in the previous comment. Although the distinction in K fixation rate between surface and subsurface soils is not vital, the high levels of organic matter within the surface horizons will cause this distinction. The organic matter can reduce the K fixation by entering the interlayer sites and expanding the layers, increasing the soil CEC, and producing organic acids, thereby dissolving the minerals and releasing their K. Other factors include the addition of K fertilizers and plant residues to the soil surface, which cause the K fixation sites to be saturated with this action (Dhaliwal et al., 2006). The problems that are described in Figs. 5 and 6 show that the rate of fixation increases as the K level applied to the soil increases, but the percentage of K fixation decreases. The findings of the statistical study also show that there is a substantial variation between the rate of added K and the degree of K fixation, as well as between the standard treatment and the treatment of wet and dry clay and the fixation of K in various soil uses (Fig. 5).

The results show that in all samples, the application of different K levels increases the fixation rate. In fact, because the quantity of K within the soil increases, the K balance shifts to the left, and a lot of K is fastened, meaning that the results of excess potassium at

Table 6 A comparison of K fixation average between wetting and drying and no wetting and drying cycles (W&D) in different land uses

| Pedon | Physiography | Soil classification | Land use | Without W&D | | With W&D | |
|-------|----------------|---------------------|----------|-------------|-------------|----------|-------------|
| | | | | Surface | Sub-surface | Surface | Sub-surface |
| 1 | Piedmont plain | Aquic Haploxeralfs | Pasture | 217 | 229 | 371 | 379 |
| 2 | Plateau | Calcic Haploxeralfs | Garden | 195 | 285 | 391 | 395 |
| 3 | Piedmont plain | Typic Calcixerepts | Fallow | 204 | 216 | 350 | 328 |
| 4 | Piedmont plain | Typic Haploxerepts | Wheat | 136 | 168 | 323 | 351 |
| 5 | Hill | Typic Haploxerepts | Forest | 154 | 114 | 336 | 278 |
| Mean | | | | 181 | 202 | 354 | 346 |
| Max | | | | 217 | 285 | 391 | 395 |
| Min | | | | 136 | 114 | 323 | 278 |

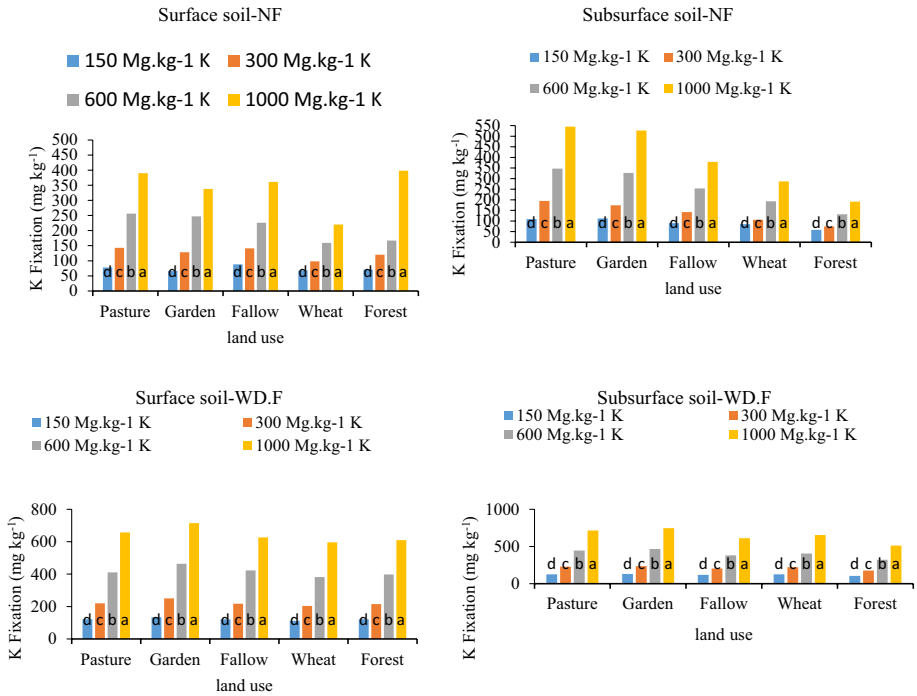


Fig. 5 K (mg/kg) value fixation by surface (0–30 cm) and subsurface (30–60 cm) soils at varying rates of application of K underwent wetting and drying treatment and regular treatment in different land uses (*WDF* fixation of wetting and drying, *NF* normal fixation)

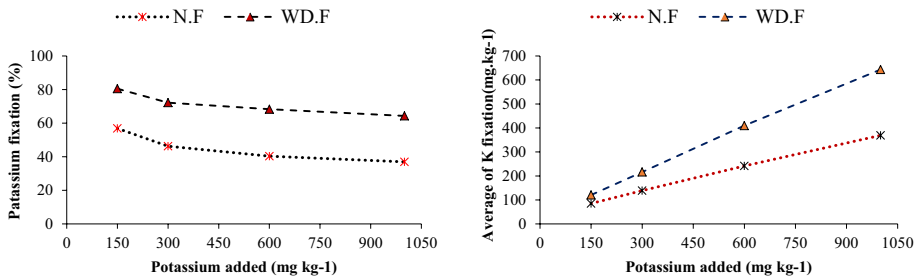


Fig. 6 Percent and cumulative K fixation with and without wetting and drying periods at varying stages of application K

the bed sites, as well as excess potassium, cause saturation. Special fixation sites K. The amount of K fixed in the soil depends on several factors, including the type and amount of clay, the particle size distribution, and the addition or removal of K from the soil (Ghiri & Abtahi, 2012). The lowest quantity of mounted K within the surface soils in all traditional and wet and dry treatments is determined within the wheat land use, and the highest amount of fixation is observed in the garden land use, which is the soil horizon of the Alfisol order. Among the studied soils, wheat land use has elevated clay and smectite contents and some vermiculite. In the fixation of soil K, these two minerals play an important role.

Since the smectite reaction to wet and dry clay is greater than that of other clay minerals and causes the mineral to expand and contract, minerals such as K can be fixed between layers during this process.

Najafi-Ghiri et al. (2019) concluded that smectites in southern Iran's calcareous soils are responsible for K fixation. As the K fixation follows the diffusion process, the K dispersion from the soil solution to the 2:1 interlayer sites increases the incubation time and wet and dry conditions. Minerals in the subsurface soils of the land uses are shown in Fig. 5; in both treatments, the lowest amount is related to the forest land use (due to high organic matter), and the highest quantity of fixation is ascertained within the garden land use, followed by the pasture land use (high clay content, especially smectite and vermiculite, and high CEC). Finally, the most important factor that reduces the fixation capacity of K by organic matter in forest land use can be the reaction between organic matter and soil K and their timely storage and release.

The findings of the bivariate association study on a variety of physico-chemical soil properties are shown in Table 7 and K fixation under the influence of normal, wet, and dry conditions at surface and subsurface horizons in different land uses. As shown in Table 7 with correlation coefficients, the amount of smectite in the soil clay element, the amount of clay, and the cation exchange of the soil were the most important factors in the fixation of K in these soils. Fixation of K includes a positive relationship ($p < 0.01$) with CEC, smectite, and clay material within the natural surroundings of wet and dry treatment. Form and clay materials had the best result on K fixation. They revealed, by comparison, no substantial relationship with the substance of soil organic matter.

Jafari and Baghernejad (2007) suggested that there is an important positive association between K fixation and cation exchange capacity (CEC). The kind and quantity of clay in most soils have the highest influence on K fixation. In the study area, smectites with different layered charges were the predominant clay minerals, and in the studied samples, small amounts of illite and vermiculite were found. Therefore, the garden land use, which has the highest amount of clay, as well as the highest amount of smectite, has the most fixation. The highest CEC of all soils was present in other land uses such as forest land use; however, fixation of K was low in them because their CEC was associated with high organic matter content. Therefore, it shows that in addition to the type and content of clay, organic

Table 7 Correlation coefficients (Pearson) for liner relationships between clay minerals and some soil properties with K (K) fixation

| | Sand | Clay | CCE | OC | CEC | Illite | Smectite | N.F |
|----------|----------|---------|--------|--------|--------|----------|----------|---------|
| Clay | -0.611 | | | | | | | |
| CCE | 0.405 | -0.045 | | | | | | |
| OC | -0.225 | 0.112 | -0.203 | | | | | |
| CEC | -0.568* | 0.675** | -0.224 | 0.204 | | | | |
| Illite | 0.369 | -0.612* | 0.050 | -0.286 | -0.414 | | | |
| Smectite | -0.530* | 0.723** | -0.010 | 0.218 | 0.465 | -0.864** | | |
| NF | -0.632** | 0.661** | -0.121 | -0.52 | 0.547* | -0.772** | 0.779** | |
| WDF | -0.779** | 0.694** | -0.352 | 0.112 | 0.575* | -0.698** | 0.737** | 0.828** |

NF normal fixation, WDF wetting and drying fixation

* $P < 0.05$; ** $P < 0.01$

matter affects the cation exchange capacity (CEC) and plays a decisive role in fixing k in different land uses.

The results of this research have significant policy ramifications for the sustainable management of land and agricultural practices. The variations in soil pH and organic carbon content among different land uses highlight the importance of tailored soil management strategies based on specific agricultural activities. Policy-makers can consider promoting soil conservation techniques, such as the adoption of cover crops, crop rotation, and organic amendments, to maintain optimal pH levels and organic carbon content in soils. Additionally, the identification of higher non-exchangeable potassium release in the forest and garden land uses suggests the need for targeted fertilizer application and nutrient management practices in these areas. Policy-makers have the opportunity to promote the adoption of precision agriculture techniques among farmers engaged in these land uses. This approach aims to achieve precise and well-balanced nutrient application, thereby mitigating the risks associated with over-fertilization and the potential contamination of the environment. Moreover, the study underscores the significance of long-term fallow practices for reducing fixation rates and enhancing nutrient availability in subsurface soils. Policy interventions can play a crucial role in promoting sustainable fallow practices and discouraging land degradation. By incorporating these policy implications, policy-makers can facilitate the adoption of sustainable soil management practices, leading to improved agricultural productivity, environmental protection, and long-term soil health.

4 Conclusion

This study demonstrates that soil properties have a significant influence on the forms of K, their release rates, and their fixation capacities. This influence varies depending on the specific land use types. Therefore, the study investigates how soil characteristics affect various land uses and how they, in turn, affect the distribution, fixation, and release of potassium. The highest concentrations of K forms were observed in wheat and garden land uses, while infertile lands under fallow and pasture land utilization exhibited reduced K liberation due to vegetation absence and consequent low organic matter content.

Furthermore, forest and garden land uses demonstrated the highest NEK release with both calcium chloride and oxalic acid extractants. These high release rates can be attributed to soil characteristics, such as NEK content, CEC, clay content (particularly smectite), and organic matter content. These differences in soil properties contributed to the disparities in K release and fixation across distinct land utilization types, probably caused by differences in land use K, type, soil evolution, and management techniques.

This study also emphasizes the suitability of the general power equation for modeling K release. The surface soils in wheat land use exhibited the lowest K fixation capacity in both normal, wet, and dry treatments, while garden land use displayed the highest fixation rate, characterized by Alfisols with high clay and smectite content, alongside some vermiculite. Forest land use had the lowest rate of fixation in subsurface soils of different land uses because of its high organic matter concentration, but garden and pasture land use had the greatest rates because of their high clay content (especially smectite and vermiculite) and CEC.

Given the heavy texture of the soils in the studied land uses, it is recommended to use K fertilizers with organic fertilizers in garden land use to mitigate K fixation. In addition, due to the observed increase in fixation, caution should be exercised when applying K

fertilizers before planting in alternating wet and dry soils. K has significant impacts on crop quality and human well-being, emphasizing the importance of these recommendations for optimizing agricultural practices.

4.1 Implications, limitations, and future directions

Identifying different rates of K fixation in different land uses emphasizes the need for appropriate fertilizer strategies. In fact, it implies that in heavy-textured soils typical of garden land use, the combination of K fertilizers with organic fertilizers can help reduce K fixation. Conversely, caution should be exercised when applying K fertilizers before planting in soils prone to alternating wet and dry conditions.

For land managers and policymakers, understanding how different land use types affect K dynamics is essential. This knowledge can be potentially used to affect land use planning, allowing agricultural productivity to be maximized while nutrient loss and environmental damage are minimized. The study emphasizes the importance of sustainable soil management practices, such as organic matter incorporation, which can counteract K fixation in specific land use contexts. These practices not only contribute to crop productivity but also contribute to long-term soil health.

Despite the valuable findings presented in this study, it is imperative to acknowledge its limitations. Firstly, this research primarily focused on specific land use systems, making its findings potentially inapplicable to other regions or soil types. Moreover, this investigation exclusively examined K release and fixation, neglecting other pivotal nutrients and factors influencing soil fertility. To achieve a more comprehensive understanding of soil dynamics, future studies should cover a wider range of land use systems and explore deeper into the intricate interactions among various nutrients.

To advance the knowledge and gain deeper insights into soil processes, future studies should consider long-term field trials. These trials can assess the impact of various management practices on nutrient release and fixation, providing valuable insights for the development of sustainable soil management strategies. Furthermore, it is essential to consider the economic implications and cost-effectiveness of different soil management approaches. This consideration is particularly important for policymakers and farmers when making informed decisions concerning land use and nutrient management practices. The study of economic analysis in future research can play an essential role in bridging the gap between scientific discoveries and their real-world application. This has the potential to develop more sustainable and efficient land use methods that ultimately increase productivity.

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Data availability Data will be made available by the first author upon request.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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