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Mineralogical Characterization of Potassium-Bearing Clay Minerals and Their Implications on K Availability in Calcareous Soils of Sulaymaniyah, Kurdistan

Rawaz Khasro Qader [1*], Akram Othman Esmail [2]

[1] Department of Pharmacy, Aynda Private Technical Institute, Erbil, 44001, IRAQ

[2] Department of Soil and Water, College of Agriculture, Salahaddin University, Erbil, 44001, IRAQ

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ABSTRACT:

The mineralogical composition and properties of potassium-bearing clay minerals are important to determine the availability of potassium (K) in the calcareous soils, but there is limited knowledge about the agricultural soils in the Kurdistan Region of Iraq. This study characterized the prevailing potassium-bearing clay minerals within agricultural soils of three representative sites in the Sulaymaniyah Governorate (Bakrajo, Pshdar, and Bitwen) and determined their effects on the K availability. Soil samples were collected from the plow layer (0 - 30 cm) and analyzed to determine the physicochemical characteristics, K fractions, and clay mineralogy by X-ray diffraction (XRD). The findings revealed that soils are slightly alkaline pH (7.41-7.82), low electrical conductivity (0.26-0.41 dS/m), and variable cation exchange capacity (16.38-48.88 $cmol_c$/kg). Soluble K was 11.5-32.07 mg/kg and exchangeable K was quite variable 191.35-448.98 mg/kg, indicating that there was a lot of spatial heterogeneity in K status. The XRD analysis identified illite was the major mineral and mixture of illite-smectite, chlorite, and expandable components of clay with varying percentages were detected across all sites. The soils of bakrajo showed mixed-layers of illite-smectite assemblages with large CEC, and moderate exchangeable K, which represented intermediate weathering. Bitwen soils exhibited a high content of expandable clay with exceptionally high exchangeable K (373.8 - 448.98 mg/kg) that could be attributed to the high levels of illite weathering and progressive release of K. Pshdar soils were highly crystalline, well-ordered illite with minimal expandable components hence the lowest exchangeable K (191.35 – 210 mg/kg) despite abundant illitic mineral content, indicating that crystallinity and structural order limits K release from interlayer positions. The results prove that K retention and availability in such calcareous soils depend on clay mineral composition, the degree of crystallinity, the weathering degree, rather than overall clay content. The nature of Pshdar soils being in need of intensive fertilization with K due to limited mineral releases of K, whereas Bitwen soils are partially able to depend on natural sources of K through continual weathering. The research will be of critical mineralogical importance in designing site-specific K management plans and achieving optimal efficiency on the fertilizer use in the semi-arid farming systems of the Kurdistan Region.

Keywords: Potassium-bearing, Clay mineralogy, X-ray diffraction, Calcareous soils.

1 INTRODUCTION

Potassium is an essential macronutrient that enhances plant growth and productivity and is involved in many physiological functions, including enzyme activation, osmoregulation, and stress tolerance [1, 2]. Despite the fact that K is among the most common elements in the earth crust, very little is accessible to plants. It is highly sensitive to the mineralogy of the soil and the shapes of K available, i.e., soluble, exchangeable, non-exchangeable, and structural [3]. A significant reservoir, which can replenish exchangeable and soluble K over time, is one of them, non-exchangeable K, which is mostly found in interlayers of micaceous clay minerals, including illite, muscovite, and biotite [4, 5]. Clay minerals significantly contribute to the dynamics of K, because the minerals can fix or release K depending on their structure, charge distribution, and the interlayer characteristics [6]. The alternating wetting and drying cycles as well as the calcareous parent materials and the management practices also affect K dynamics in soils in semi-arid and

*Corresponding author: rawazz.qader@gmail.com

Mediterranean areas such as in the Kurdistan Region of Iraq [7]. Despite this K recognition in sustainability crop production, there has been little research done in Kurdistan Region, much of the research done has focused on bulk soil K status rather than mineralogical forms and processes which control K retention and release.

It is important to understand the characterization of K-bearing clay minerals to predict the long-term K-supplying capacity of soils and bring the best practice of fertilizer administration [3, 8]. Such advanced methods of analysis as X-ray diffraction (XRD), scanning electron microscopy (SEM), and X-ray fluorescense (XRF) can be used to identify and determine the amount of K-bearing clay minerals, which enhances our comprehension of how the mineral composition influences K availability [9, 10]. Combining mineralogical characterization and chemical K fractionation can be used to determine the contribution of several K pools and their interaction in the soil matrix [4, 6]. Agricultural soils found in the Sulaymaniyah region are significant to the food security in the region but little data exists on the mineralogical character of K-bearing phases. It is important to characterize these clay minerals thus in a bid to enhance the management of soil fertility and enhance sustainable agricultural productivity. This paper will name and describe the prevailing K-carrying clay minerals in Sulaymaniyah agricultural soils located in the Kurdistan Region, and evaluate its consequences on the availability of K and its nutrient management of the soil.

The purpose of this study was to: (1) characterization and identification of the major clay mineral constituents found in agricultural soils of Sulaymaniyah with the help of XRD; (2) assess the spatial variability of physicochemical properties of the soils and K fraction depending on the location; (3) establish the relationship between the mineral composition, crystallinity, and availability of K; and (4) provide mineralogical background to develop site-specific K management strategies to enhance the sustainable agricultural productivity in Sulaymaniyah Region.

2 MATERIALS AND METHODS

2.1 STUDY AREA AND SAMPLING

The research was carried out in three representative farms in Sulaymaniyah Governorate, Kurdistan Region: Bakrajo, Pshdar and Bitwen (Figure 1). These areas were chosen to portray the various soils and agricultural activities in the area. A total of three soil samples were taken out of the plow layer (0 - 30 cm) of each location in the spring of 2023. The samples were collected and then dried in air over a period of 48 hours, sieved using a 2 mm sieve to eliminate debris and stones and stored in clean plastic containers until further processing in the laboratory.

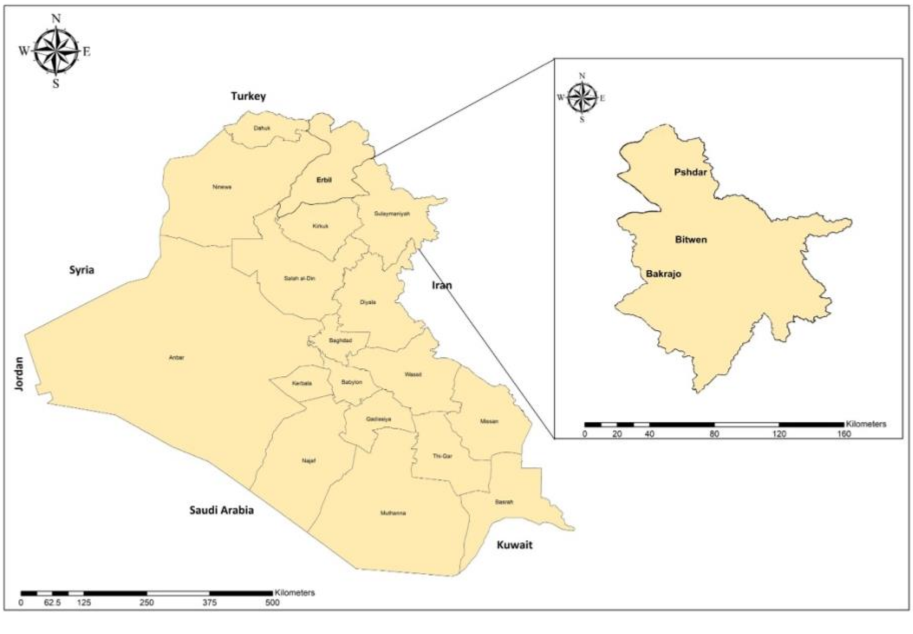

FIGURE 1. Map of the study area (Sulaymaniyah, Kurdistan Region) and illustrating the locations of soil sampling sites at depths 0-30 cm across agricultural lands (map source: Google Maps).

2.2 SOIL CHEMICAL ANALYSES

Soil pH and electrical conductivity (EC) were measured using standard electrodes in 1:1 and 1:5 soil:water extracts, respectively [11]. Cation exchange capacity (CEC) was determined using sodium acetate method at pH 7.0 [12]. Organic matter (OM) content was analyzed using the Walkley-Black oxidation technique [13]. Organic carbon (OC) was subsequently calculated from OM values using the conventional conversion factor, based on the assumption that soil organic matter contains approximately 58% organic carbon (OC = OM × 0.58), following standard soil science methodology. The total nitrogen (N) was analyzed using the Kjeldahl digestion technique [14]. The total and active calcium carbonate ($CaCO_3$) were determined by the methods of calcimeter and oxalate, respectively [15]. All the soil samples were taken in the Sulaymaniyah agricultural fields.

2.3 POTASSIUM ANALYSIS

Distilled water (1:5 soil:water) was used to extract soil soluble K (Ksol) and 1 M ammonium acetate (pH 7.0) was used to extract exchangeable K (Kex). The flame photometry was used to measure K concentrations in the extracts [16]. Recent investigations have shown that biochar is relevant in increasing K in soils, and this means that it is involved in the increase in both water-soluble and exchangeable K fractions [17].

2.4 MINERALOGICAL ANALYSIS

The Clay-sized particles (<2 μm) were isolated by sedimentation, and oriented mounts were prepared on glass slides. The X-ray diffraction (XRD) analysis was performed on a PANalytical X'Pert PRO diffractometer (Cu Kα radiation, λ = 1.5406 Å) in the scanning range of 4° to 17° 2θ, 0.04o step size and 2 s counting time. The samples were analyzed in three conditions (1) air-dried and Mg-saturated; (2) solvated with ethylene glycol; and (3) K-saturated and heat at 530oC. The identification of clay minerals was performed in line with the standard procedures [18]. New developments on XRD have been able to give a more conspicuous understanding on the identification of clay minerals, which leads to stronger accuracy of mineralogical evaluation [19].

3 RESULTS

3.1 SOIL CHEMICAL PROPERTIES

The chemical composition of the agricultural soils across all sites provided significant variability which indicates the parent material, the degree of weathering and the management activities of the soils (Table 1 -3).

3.1.1 SOIL pH AND ELECTRICAL CONDUCTIVITY

The pH of the soil ranged between 7.41 and 7.82 in all sites, indicating slightly to moderately alkaline which is typical of semi-arid calcareous soils found in the Kurdistan region. Such alkalinity is caused by the existence of calcium carbonate and also because of low leaching due to climatic conditions. The values of electrical conductivity (EC) were consistently low (0.2624-0.4101 dS/m), indicating non-saline conditions with minimal salt accumulation. Bakrajo exhibited slightly higher EC values (0.2995-0.4101 dS/m) compared to Pshdar (0.2624-0.3097 dS/m) and Bitwen (0.3054-0.3301 dS/m) which might have been due to the fertilizer application or the quality of irrigation water.

3.1.2 CATION EXCHANGE CAPACITY

The values of CEC were quite different among locations, Bakrajo showed the highest values (29.28 - 48.88 $cmol_c$/kg), followed by Bitwen (24.64 - 27.70 $cmol_c$/kg) and Pshdar had the least values (16.38 - 21.02 $cmol_c$/kg). The elevated CEC of Bakrajo indicates greater abundance of the negatively charged surfaces which could be related to 2:1 clay mineral such as illite, vermiculite, or smectite. This improved potential has significant consequences to K retention and availability. The lower CEC in Pshdar site suggests either reduced in clay content, dominance of low-activity clays, or dilution effects from higher carbonate content.

3.1.3 ORGANIC MATTER AND NITROGEN CONTENT

The content of OM was relatively low (0.6 to 2.16%) which is characteristic of semi-arid agricultural soils where high temperatures promote decomposition. The highest levels were registered by Bakrajo (1.58 - 2.16%), then Bitwen (1.1 - 1.7%) and Pshdar (0.6 - 0.98%). The total nitrogen (N) had comparable pattern, between 0.02% to 0.08% with the highest of 0.08% at Bakrajo. Such low concentrations indicate the possibility of N deficiency and require N fertilization of crops to sustain optimum yields.

3.1.4 CALCIUM CARBONATE CONTENT ($CaCO_3$)

The total $CaCO_3$ was also different: Bakrajo (23.18 - 25.98%), Bitwen (19.52 - 20.38%), and Pshdar (13.26 - 17.55%). The active $CaCO_3$ level was ranged between 10.5% to 22.4%, representing 66-82% of the total carbonate. This high proportion of reactive carbonate affects the phosphorus availability, pH buffering ability, and solubility of micronutrients, and a significant implication on K dynamics and stability of clay minerals.

3.1.5 SOLUBLE AND EXCHANGEABLE POTASSIUM

The soluble K ranged from 11.5 to 32.07 mg/kg, with Bitwen giving the highest levels (26.70 – 32.07 mg/kg), considerably exceeding Bakrajo (11.50 - 18.52 mg/kg) and Pshdar (16.82 – 18.00 mg/kg). The high soluble K in Bitwen indicates recent fertilization, increased rates of weathering of K-bearing minerals, or some better conditions of K release.

There was a substantial variation in exchangeable K: Bitwen displayed remarkably very high values (373.80 - 448.98 mg/kg), which was considerably higher than Bakrajo (255.55 - 346.41 mg/kg) and Pshdar (191.35 – 210.00 mg/kg). The ratio of exchangeable:soluble K was between 10:1 and 25:1 and this was a sign of high buffering capacities of all sites.

3.2 POTASSIUM AVAILABILITY ASSESSMENT

The soil fertility guidelines specify that exchangeable K less than 200 mg/kg is marginal to being deficient in high yielding crops. Whereas Bitwen demonstrated sufficient to high levels of K, Pshdar displayed borderline levels of exchangeable K, and all sites demonstrated low levels of soluble K. Such results indicate that crop requirements cannot be addressed through intensive cultivation without supplemental fertilization of the land. The negative correlation between the content of carbonate and exchangeable K implies that the mineralogy of the clay, the stages of weathering, and the history of the management take leading positions in the determination of K availability.

3.3 CLAY MINERALOGY AND POTASSIUM DYNAMICS

The high CEC in Bakrajo is indicative of 2:1 clay minerals (illite, vermiculite or mixed-layer illite-smectite), which are the major sources of non-exchangeable and structural K. The moderate CEC in Bitwen together with extremely high exchangeable K indicates that there are clay minerals in advanced stages of weathering, where interlayer K progressively released from by illite or biotite, or reflects intensive K fertilization history. Low CEC and K of Pshdar is related to low clay content, preponderance of low-activity clays, or dilution by carbonate content, resulting in limited capacity to retain and supply K.

3.4 SOIL FERTILITY MANAGEMENT IMPLICATIONS

The fact that there is a lot of spatial variation in the K status implies that fertilizer needs site-specific advice. Pshdar soils have higher frequency of K application because of low buffering capacity and marginal K contents, whereas Bitwen can be less intensively fertilized in the short term. Alkaline pH and the abundance of carbonates can modify the fixation of K processes, and thus the OM additions would be advantageous to enhance the CEC and K fixation. The correlation between CEC and K retention affirms that clay mineralogy is an important factor in the supply of K in the long term. The soils with a preponderance of illitic minerals (Bakrajo) have large reserves of non-exchangeable K, but have low release rates in seasons of maximum crop growth, which require additional manure. The reason why soluble K levels are low at all sites even though in certain sites exchangeable K levels are moderate to high points to the need to ensure sufficient levels of soluble K are maintained during critical growth periods by split applications of fertilizer. These associations between soil attributes and K processes are crucial towards devising sustainable nutrient management techniques that retain soil fertility and maximize the efficiency of the fertilizer use in the Sulaymaniyah region.

Table 1. Analytical results of soil samples collected from Bakrajo, Sulaymaniyah Region, Kurdistan.

Location	Bakrajo									
Sample No.	**pH**	**EC**	**CEC**	**OM**	**OC**	**N**	**Total $CaCO_3$**	**Active $CaCO_3$**	**K_{sol}**	**K_{ex}**
	Value	**dS/m**	$cmol_c/kg$				**%**			**mg/kg**
S_{BK-1}	7.66	0.3308	32.49	1.62	0.94	0.04	25.66	20.5	14.24	276.9
S_{BK-2}	7.63	0.4101	48.88	2.16	1.05	0.08	23.18	22.4	18.52	346.41
S_{BK-3}	7.81	0.2995	29.28	1.58	0.91	0.04	25.98	21.5	11.5	255.55

Table 2. Analytical results of soil samples collected from Pshdar, Sulaymaniyah Region, Kurdistan.

Location	Pshdar									
Sample No.	**pH**	**EC**	**CEC**	**OM**	**OC**	**N**	**Total $CaCO_3$**	**Active $CaCO_3$**	**K_{sol}**	**K_{ex}**
	Value	**dS/m**	$cmol_c/kg$				**%**			**mg/kg**
S_{PD-1}	7.81	0.3097	20.44	0.64	0.37	0.08	13.26	10.5	16.82	191.35
S_{PD-2}	7.73	0.2624	16.38	0.6	0.35	0.06	17.55	13.5	17.05	205.5
S_{PD-3}	7.65	0.3016	21.02	0.98	0.42	0.06	16.5	13	18	210

Table 3. Analytical results of soil samples collected from Bitwen, Sulaymaniyah Region, Kurdistan.

Location	Bitwen									
Sample No.	**pH**	**EC**	**CEC**	**OM**	**OC**	**N**	**Total $CaCO_3$**	**Active $CaCO_3$**	**K_{sol}**	**K_{ex}**
	Value	**dS/m**	$cmol_c/kg$				**%**			**mg/kg**
S_{BT-1}	7.82	0.3054	24.95	1.56	0.7	0.03	19.52	13	30.12	421.68
S_{BT-2}	7.41	0.3108	24.64	1.1	0.64	0.02	20.38	13.5	26.7	373.8
S_{BT-3}	7.8	0.3301	27.7	1.7	0.88	0.05	19.87	14	32.07	448.98

3.5 X-RAY DIFFRACTION (XRD) ANALYSIS RESULTS

The use of XRD of oriented clay specimens under three treatments (air-dried Mg-saturated, ethylene glycol solvation, and K-saturated heated to 530°C) revealed the presence of different clay mineral assemblages across all sites.

3.5.1 BAKRAJO SAMPLES (SBK-1, SBK-2, SBK-3)

The Bakrajo exhibiting a strong peak of 10 Å indicating illite as the dominant clay mineral across these samples. The existence of this peak even after heating to 530oC proved the presence of illite with K fixed in interlayer positions. Another peak (14 Å) that shifted to approximately 17 Å with ethylene glycol treatment, revealed a mixed-layer illite-smectite. SBK-2 had the most prominent expandable component. Additional 7 Å peak reflections stable through all treatments indicated the presence of chlorite. This miced-layer, illite-smectite assemblage is the reason behind the large CEC values (29-49 meq/100g) and offers high reserves of non-exchangeable K. These results are in analogy with other mineralogical investigations in the Iraqi soils made before. [20] also described comparable clay mineral assemblages in east Erbil clay deposits that were dominated by illite, chlorite, and palygorskite. On the same note, [21] reported the occurrence of chlorite, smectite, mixed-layer minerals, illite, and kaolinite in the folded zone of Kurdistan Region. The presence of illite and mixed-layer illite-smectite in Bakrajo samples indicates moderate weathering conditions as a characteristic of semi-arid environment, when some micaceous minerals partially transformed into expandable phases [22].

3.5.2 BITWEN SAMPLES (SBT-1, SBT-2, SBT-3)

Bitwen samples showed high 10 Å illite peaks, which were not as strong as those of Bakrajo. The expandable component of clay (14 Å → 17 Å with ethylene glycol treatment) was more emphatic especially in SBT-2 and SBT-3 samples, indicating greater smectite or vermiculite. This is the reason of such high exchangeable and expandable clays hence the moderate CEC and exceptionally high exchangeable K in these soils, probably caused by partial weathering of illite to expandable clays that gradually release inter-layer K. The 7 Å reflection was weaker than the other sites suggesting lower chlorite content. The increase and expandable levels of clay content and the corresponding high exchangeable K in Bitwen are in line with global observations of the K dynamics within the weathered soils. As shown by [23], smectite:illite ratio has a strong impact on plant-available K, with a high amount of smectite affecting the exchange of K. In the same way, [1] observed that 2:1 clay minerals, including smectite, have the ability to absorb K^+ in potassium-rich environments and release it during plant uptake as a result of cation exchange reactions. Bitwen samples are mineralogically indicative of high levels of weathering copared to ither sites, and this coincides with progressive signs of illite degradation in agricultural soils [24].

3.5.3 PSHDAR SAMPLES (SPD-1, SPD-2, SPD-3)

Pshdar samples, especially SPD-2 exhibited intense 10 Å peak, which is an indication that it contained a very high level of well-crystallized illite. Nevertheless, the sharp, intense peak indicates low level of surface area and minimal inter-layer expansion capacity. This highly crystalline illite resisting weathering and release of K, and thus it is not surprising that Pshdar has the lowest exchangeable K and CEC even though it has abundant illitic minerals. The expandable clay peak was minimal (14 Å), indicating limited amount of smectite. Significant peaks of 7 Å indicated that there were large amounts of chlorite which contribute to lower overall CEC. Highly crystalline, poorly expandable illite characteristic of Pshdar is a significant limitation to K availability. [3] discovered that well-crystallized illitic clays fix K between layers during drying cycles and release the K incompletely on rewetting making it difficult to manage K in agricultural systems. The sharp XRD peaks that observed in SPD-2 sample, suggest an absence of structural disorder and limited weathering, which limits the K release of inter-layer positions [25]. This mineralogical characteristic was attributed to the seeming contradiction between high overall illite content and low exchangeable K in Pshdar soils, which was also reported by [26] in calcareous soils of Iran where illite-dominated clay fractions had small amounts of K, but large amounts of mineral K.

3.6 MINERALOGICAL IMPLICATIONS FOR POTASSIUM DYNAMICS

The XRD results explained the patterns of K availability across all sites. The illite-smectite mixed-layer form in Bakrajo provides a high CEC and moderate exchangeable K with substantial long-term reserves and this is comparable to the findings of [20] on the soils found in Kurdistan Region. The increased proportion of expandable clay in Bitwen makes the exchange of K easier and more liberated and results in good proportions of exchangeable K formed by progressive weathering of illite, also well-documented in the literature on agricultural soils [1, 23]. Non-expandable illite crystal as in Pshdar takes up K in structural positions to form low exchangeable K despite having a large quantity of mineral K in the soil as was found by [3] in illite-dominated soils. These mineralogical differences demonstrate that there are variations in the weathering stages at the study sites. Bakrajo represents the intermediate weathering in which the conversion process of illites to smectites is still in process, Bitwen is the advanced weathering in which the illites are more debased and the primary minerals are resistant and K is not readily available. The variation in the clay mineral composition within the relatively small area of Sulaymaniyah was reflects the influence of the local factors on the formation of the soils, including the composition of the parent material, variations in microclimate, and land use history on pedogenic processes [21, 22]. The outcomes of these investigations confirm the fact that K availability and retention in such soils of agriculture is regulated by the mineral composition and crystallinity of the clay besides the overall clay content. The recent study can support this conclusion, as it has found that the K release of the phyllosilicate minerals is in the following order: biotite > vermiculite > illite > smectite > muscovite [27]. The practical implications of the experiment on K fertilization of Sulaymaniyah soils include the following: Pshdar soils require more intense K fertilization due to a low mineral K release and the Bitwen soils are more likely to rely upon the native K releases in the course of the weathering process with Bakrajo taking an intermediate position.

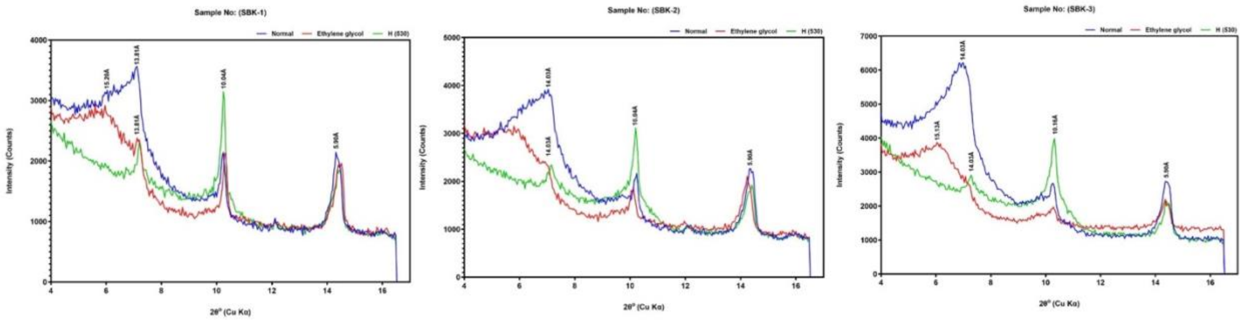

FIGURE 2. **XRD Mineralogical Analysis of Soil Samples of Bakrajo Region.**

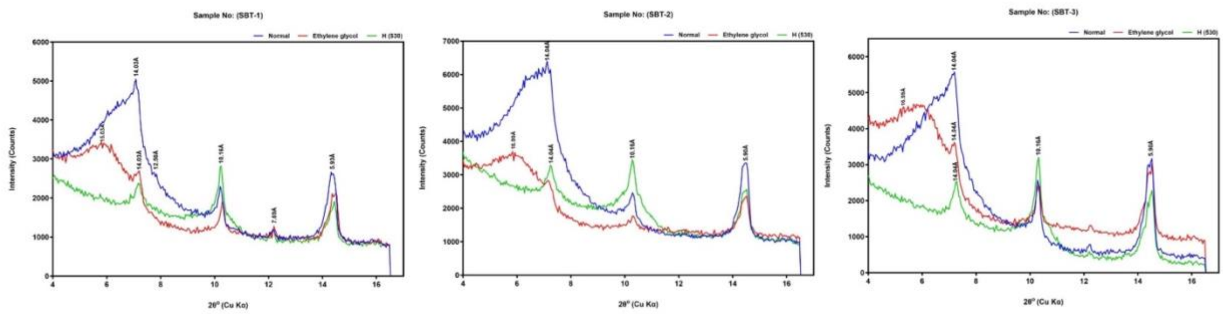

FIGURE 3. **XRD Mineralogical Analysis of Soil Samples of Bitwen Region.**

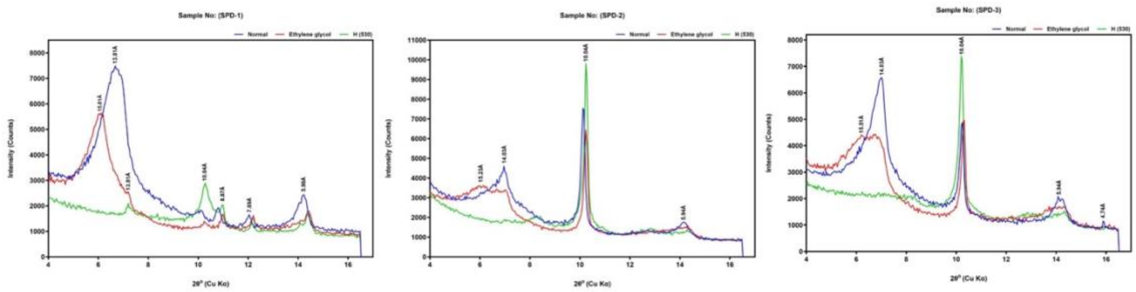

FIGURE 4. **XRD Mineralogical Analysis of Soil Samples of Pshdar Region.**

4 DISCUSSION

4.1 CORRELATION BETWEEN CLAY MINERALOGY AND POTASSIUM AVAILABILITY.

The XRD findings have given mechanistic explanations of the patterns of availability of K observed at the sites of the study. The unique composition of clay minerals in each site gives rise to entirely different K dynamics with direct agricultural management implications.

The illite smectite mixed-layer assemblage that was determined at Bakrajo can be compared to the results of [20], who described such distributions of clay minerals in soils east of Erbil. This mineralogical composition offers good CEC and exchangeable K with large long-term K reserves. The semi-weathering conditions that are typical of semi-arid environments are represented by the partial smectite formation out of illite [22]. Expandable sites between the layers are

available with the option of retaining and releasing K gradually to form a balanced system of maintaining continuous supply of K.
The high content of expandable clay and the resultant high content of exchangeable K are in line with the world on K dynamics in weathered soils. [23] have shown that the proportion of smectite to illite has a strong effect on plant-available K, and the higher the smectite proportion among them, the more vigorous the K exchange processes. [1] reported that 2:1 clay minerals, such as smectite, have the ability to absorb K + in potassium-rich conditions and lose it during plant uptake in cation exchange reactions. According to the Bitwen mineralogy, there was an indication of high levels of weathering than in other locations, which is in agreement with progressive trends of degrade illites in agricultural soils [24]. This high weathering condition results in good availability of K conditions, but could reflect on depleting long term K supply.

The illite of Pshdar is highly crystalline and poorly expandable which is a major limiting factor to the availability of K. [3] discovered that illicitic clays that are well-crystallized retain K in interlayers of drying cycles and not fully released when rewet, making it difficult to manage K in agricultural systems. The distinct XRD peaks of S_PD-2 indicate that there is a small amount of disorder in the structure and little weathering, limiting the release of K in the interlayer sites [25]. This mineralogical feature can be used to describe the observed paradox regarding great overall illite content and low exchangeable K at Pshdar, which also was found by [26] in Iranian calcareous soils with illite-dominated clay fractions having high mineral K content but low K availabilities.

4.2 COMPARISON TO REGIONAL AND GLOBAL STUDIES.

The clay mineral assemblages observed in this research paper are similar to past mineralogical researches in the Iraq soils. [21] indicated that chlorite, smectite, mixed-layer minerals, illite, and kaolinite were present in the folded zone of Kurdistan Region, which showed that variety of clay mineral assemblages could be found in a relatively small geographic area. The difference in the composition of clay minerals in Sulaymaniyah demonstrates the impact that the local factors such as the composition of parent materials, microclimatic diversity, and the history of land use exert on the formation of the soil [21, 22]

Our results are in line with findings made by [27], who have determined that K release by phyllosilicate minerals is in the following order: biotite > vermiculite > illite > smectite > muscovite. The prevalence of illite in all sites and the different percentage content of expandable ones justify the noted progressive decrease in the availability of K in Bitwen (the highest) and Bakrajo (the intermediate) to Pshdar (the lowest).

4.3 POTASSIUM AVAILABILITY TEST AND FERTILITY CONSEQUENCES.

Based on the soil fertility standards, the exchangeable K of less than 200 mg/kg is marginal with regard to high yield crops. Bitwen had shown adequate levels of K up to high K levels whereas Pshdar reflected borderline levels of exchangeable K. The soluble K levels of all sites were low, which suggests that crop needs cannot be achieved in terms of intensive cultivation with no addition of fertilizers.

The antagonistic association between the carbonate content and exchangeable K indicates that the exchangeable K is affected more by clay mineralogy, weathering stage, and management history than by the carbonate content. The Bakrajo CEC suggests that there are large amounts of 2:1 clay minerals (illite or vermiculite or mixed-layer illite-smectite) which are the primary sources of non-exchangeable and structural K. The moderate CEC of Bitwen and very high exchangeable K indicate clay minerals at advanced stages of weathering, and K interlayer had gradually been released by illite or biotite, or indicates a record of intensive K-fertilization. Low CEC and K at Pshdar are associated with small amounts of clay, presence of lower-activity clays, or effects of carbonate dilution and hence a low ability to retain and provide K.

4.4 IMPLICATIONS ON SITE-SPECIFIC POTASSIUM MANAGEMENT.

The large spatial range in the status of K requires individual site-based fertilizer recommendations. Low buffering capacity and marginal K contents necessitate more frequent K applications in Pshdar soils, but low buffering capacity and high buffering capacity mean that Bitwen soils can be managed less intensively in the short term. The high PH and high concentration of carbonate can alter the process of K fixation; hence, addition of organic matters would be advantageous in the improvement of CEC and K fixation.

The association of CEC and retention of K proves that clay mineralogy is a paramount consideration in the long-term supply of K. Sols containing illitic minerals as the major ones (Bakrajo) are rich in non-exchangeable K but could have slow-release rate during the highest crop growth and thus require additional fertilization. The fact that soluble levels of K are low in all locations including where exchangeable K is intermediate to high highlights the importance of split applications of fertilizers to ensure sufficient soluble K levels in times of high growth.

4.5 THE NEXT STAGE IS THE INTERPRETATION OF WEATHERING.

The mineralogical variations that are seen depict different weathering conditions among the areas of study. Bakrajo is a representation of an intermediate weathering, whereby the process of transforming illite to smectite is in active progress. Bitwen also has evolved weathering with more degraded illites and progressive release of K. Pshdar exhibits insufficient weathering and resistant primary minerals and low availability of K. These observations are in agreement with the sequential weathering model of clay minerals which is put forward in semi-arid calcareous environments [22].

CONCLUSION

The paper has outlined the clay minerals K-bearing in soils of agriculture in Sulaymaniyah, Kurdistan Region, and established that a high degree of mineralogical variability exists that governs the availability of K. XRD was utilized to establish the assemblage of the clay mineral in three sites and found that the various sites had distinct distribution of the different clay minerals: Bakrajo was mixed-layer illite-smectite, high CEC (29-49 meq/100g) and moderate K content; Bitwen exhibited higher clay content, progressive illite weathering, and, therefore, high exchangeable K (374-449 mg/kg): Pshdar requires intensive K fertilizer since it might be losing a fixed quantity of mineral K, whereas Bitwen can rely more on native ones in the shape of progressive weathering. The fact that the soluble K in all sites is relatively low, means that some form of further fertilization must be applied at the times of greatest demand of the crops. Critical information regarding the soil mineralogy and K dynamics in the Kurdistan Region is provided in the present study, which is a basis of the sustainable fertility management practices. To comprehend the seasonal dynamics of K releases and long-term effects of the management activities on the transformation of clay minerals and power of K providing in these semi-arid calcareous soils, future research needs to be done to establish the dynamics of K release.

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CONFLICTS OF INTEREST

The author declares no conflict of interest.

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