Soil potassium adsorption at several shallot center areas, Brebes Regency, Central Java Province

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Abstract

Brebes Regency, Central Java, is one of Indonesia's most important shallot production centers implementing intensive agriculture. In the bulb production, K is needed more than other nutrients. This study aimed to assess and describe the adsorption characteristics of K on the soils of the shallot farming system in Brebes District, Central Java. Soil samples were collected at several locations in the shallot center areas of Brebes Regency, Central Java Province. The observed soil properties included pH H2O, EC, soil texture, organic C, potential-K, exchangeable Ca, Mg, Na, and K, CEC, exchangeable Al and H, and water-soluble K. K adsorption was simulated by the Freundlich equation. The proportion of K from low to high of retention energy in the soil studied had the order, namely water-soluble K<exchangeable K<potential-K. The K adsorption result showed that the soil had a high capacity to adsorb K. It indicated that added K was accumulated in the soil. The high capacity to adsorb K indicated that K accumulated in Brebes with continuous K fertilization. This research recommended that to increase the efficiency of K fertilizer, it is necessary to introduce the technology to mine K in Brebes soils like bacteria capable of dissolving K or biofertilizers.

Keywords: Freundlich model, shallot bulb, soil potassium

Introduction

From 2010-2019, Central Java has consistently been the most significant contributor to national shallot production (38.2% on average). However, the growth rate of shallot (Allium asecaloncium L.) production in Central Java during this period was -0.55% (Adiyoga, 2020). Brebes Regency, Central Java, is one of Indonesia's most important shallot production centers that applies intensive agriculture, including fertilization. Fertilization is an essential factor in shallot productivity. Farmers in this area grow shallots four times yearly or interspersed with other crops (e.g., chili, eggplant, soybeans, corn, rice) or fallow (Muliana et al., 2018a). Farmers tend to use excessive amounts of fertilizers, including potassium (K) fertilizers, to ensure crop production without considering the number of nutrients in the fertilizers and the current soil nutrient status. The impact of this activity is shown by the high residual K in the shallot planting areas in Brebes Regency (Muliana et al., 2018b). From the perspective of root crops, K is more needed than other nutrients (Sumiati and Gunawan, 2007). K content in the bulb increased the quality of the bulb and shelf life. Furthermore, bulb remains solid even it is stored for a long time (Gunadi, 2009).

However, K fertilization needs to be done according to plant needs based on soil characteristics to minimize adverse environmental impacts (Di Gioia et al., 2017). K explicitly affects plant growth. K participates not only in the transport and absorption of nutrients but also provides resistance to abiotic and biotic pressures,
affecting crop production and quality. K derived from mineral weathering is retained in K pools with different availability. The balance of K in the interlayer, surfaces, and edges of the clay mineral crystal lattice and K in the soil solution influences the adsorption potential of soil K. The mobility of soil K is affected by the dynamic balances in the soil system. This dynamic balance is influenced by the type of clay minerals, pH, soil organic matter (SOM), soil moisture, cation exchange capacity (CEC), fertilization, and tillage systems (Pal et al., 1999; Pannu et al., 2003; Wakeel et al., 2013).

Most of the K is in the interlayer adsorption of clay minerals (Harter and Naidu, 2001) or lost through leaching, so it is not available for direct plant absorption. Among the types of clay minerals that affect the dynamic balance, illite, vermiculite, and smectite, were found to have a positive association with the amount of adsorbed K. Therefore, the behavior of K supplied through fertilizers varies from soil to soil, and the response of plants to applied K is unpredictable due to different soil adsorption characteristics (Kibreselassie et al., 2018; Misskire et al., 2019).

Alluvial (Inceptisols), Mediterranean (Alfisols), and Grumusol (Vertisols) soil types are soil types in Indonesia that are widely used for agriculture (Subagyo et al., 2000; KEMENTAN-RI, 2020) including in Brebes Regency. The characteristics of these soils generally contain 2:1 type clay minerals, which include having a high clay fraction (33-92%) and a neutral to alkaline soil reaction, namely a pH of around 6.5-8.0. Soil acidity is low, so the availability of micronutrients (Fe, Cu, Zn, and Mn) is generally low. Organic matter is low to moderate, and potential K, bases (Ca and Mg), and cation exchange capacities are generally high (Subagyo et al., 2000).

Adsorption of K in the soil, namely the transformation of available forms of K into unavailable ones, can affect the effectiveness of fertilization in soil-plant systems. Understanding the mechanisms involved in K adsorption in the soil is significant in soils dominated by 2:1 type clay minerals which have the potential to be mobilized by soil chemical weathering (Murashkina et al., 2007; Simonsson et al., 2009). K adsorption in the soil is quite complex and cannot be explained by a single, simple reaction. Several equations or isotherms of K adsorption in soil have been developed, one of which is the Freundlich adsorption isotherm, to describe the relationship between the fixed amount of K per unit weight of soil and the concentration of K in solution. This approach is used to evaluate plant nutrient requirements for optimal growth. The factors of quantity, intensity, and capacity are essential for estimating the number of soil nutrients required for plant growth.

Many studies have been carried out on agricultural land in Brebes Regency, including the use of pesticides that have the potential to reduce soil quality (Joko et al., 2017), management and fertilization of phosphorus and potassium (Muliana et al., 2018b), evaluation of shallot land suitability (Rahayu et al., 2018), harvesting of soil phosphorus residues (Muliana et al., 2018a), information on the distribution of heavy metals (Dewi et al., 2021), the ability of indigenous bacteria to become bioremediation agents for pesticides (Istiqomah et al., 2021), and the effect of adding gypsum and zeolite on soil characteristics and shallot growth with saline irrigation (Rahayu et al., 2021). However, studies on soil K adsorption are limited in Brebes Regency, Central Java, especially in shallot cultivation. Thus, this research is considered necessary as a basis for evaluating the ability of the soil to provide K for plants, predicting the fate of K fertilizer added to the soil, and making appropriate K fertilization recommendations. It can also describe the exchange of K from the soil by other ions, mainly Ca and Mg. Furthermore, synthetic fertilization can be carried out correctly. It can reduce synthetic K fertilizers by taking actions that utilize K residues, especially biologically, to reduce the negative impact on the environment to support sustainable agriculture. Therefore, this study aimed to assess and describe the adsorption characteristics of soil K under shallot farming systems in Brebes District, Central Java, Indonesia.

Materials and Methods

Study location

The study was conducted in Brebes Regency, Central Java Province, Indonesia, from November 2021 to September 2022. Coordinate information and soil subgroup at each soil sampling site are shown in Table 1. Based on data from 2021, the total rainfall was 2,689 mm, with the highest occurring in February, which was 483 mm (BPS Kabupaten Brebes, 2022). There were about 244 rainy days, the most in February and November at 28 and 30 days, respectively. Inceptisol (USDA Soil Taxonomy classification) is the dominant soil order at the study site. Shallot production in Brebes Regency in 2021 was 3,410,565 quintals, lower compared to 2020 of 3,835,111 quintals.

Soil sampling and chemical analysis

Soil samples were collected in nine locations of shallot field located in Brebes Regency. The soil samples were collected in Wanasari and Bulakamba Districts, Brebes Regency, Central Java Province. The locations were collected based on the high intensity of land use for shallots. Soil sampling for analysis of the chemical and physical properties of the soil was carried out randomly and compostely at a depth of 0-30 cm. All soil samples were air-dried, crushed, and sieved to pass a 2-mm sieve for analysis of soil physicochemical properties and adsorption studies. Soil analysis was conducted on soil characteristics that were thought to be closely related to the dynamics of K in the soil.
Table 1. Coordinate data, land use, and soil subgroup at each soil sampling location

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Coordinate</th>
<th>Village</th>
<th>District</th>
<th>Soil Subgroup*</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>S 06°52'07.48&quot; E 109°02'37.02&quot;</td>
<td>Padasugih</td>
<td>Brebes</td>
<td>Gleisol Eutrik (Typic Endoaquepts)</td>
</tr>
<tr>
<td>B2</td>
<td>S 06°52'43.13&quot; E 109°01'40.73&quot;</td>
<td>Siasem</td>
<td>Wanasaari</td>
<td>Kambisol Gleik (Aquic Eutrudepts)</td>
</tr>
<tr>
<td>B3</td>
<td>S 06°54'04.55&quot; E 109°01'10.32&quot;</td>
<td>Sidamulya</td>
<td>Wanasaari</td>
<td>Gleisol Eutrik (Typic Endoaquepts)</td>
</tr>
<tr>
<td>B4</td>
<td>S 06°51'43.26&quot; E 109°01'01.54&quot;</td>
<td>Pesantunan</td>
<td>Wanasaari</td>
<td>Kambisol Gleik (Aquic Eutrudepts)</td>
</tr>
<tr>
<td>B6</td>
<td>S 06°51'46.41&quot; E 109°00'30.54&quot;</td>
<td>Klampok</td>
<td>Wanasaari</td>
<td>Gleisol Eutrik (Typic Endoaquepts)</td>
</tr>
<tr>
<td>B7</td>
<td>S 06°52'47.66&quot; E 109°00'18.15&quot;</td>
<td>Siasem</td>
<td>Wanasaari</td>
<td>Gleisol Eutrik (Typic Endoaquepts)</td>
</tr>
<tr>
<td>B8</td>
<td>S 06°52'24.73&quot; E 109°59'43.08&quot;</td>
<td>Luwungragi</td>
<td>Bulakamba</td>
<td>Gleisol Eutrik (Typic Endoaquepts)</td>
</tr>
<tr>
<td>B9</td>
<td>S 06°55'17.54&quot; E 108°58'24.82&quot;</td>
<td>Tegalglagah</td>
<td>Bulakamba</td>
<td>Gleisol Eutrik (Typic Endoaquepts)</td>
</tr>
<tr>
<td>B10</td>
<td>S 06°50'39.60&quot; E 109°03'06.15&quot;</td>
<td>Pagejugan</td>
<td>Brebes</td>
<td>Gleisol Eutrik (Typic Endoaquepts)</td>
</tr>
</tbody>
</table>

*Brebes Regency Soil Map with a scale of 1:50,000 (ICALRD, 2017).

The soil properties, including pH H$_2$O and EC, were determined using a soil-to-water mixture of 1:5, the soil texture of the three fractions using the pipette method, organic carbon (C) was determined by Walkley and Black method, potential K using the 25% HCl method, exchangeable calcium (Ca), magnesium (Mg), sodium (Na), and K, and the cation exchange capacity (CEC) was extracted using a solution of 1 mol L$^{-1}$ NH$_4$OAc pH 7.0, water-soluble K using soil to water mixture of 1:5, then shaken for five minutes, and exchangeable aluminium (Al) and hydrogen (H) were extracted using KCl 1 mol L$^{-1}$. The final solutions of Ca and Mg were measured using a Shimadzu AA-6300 atomic absorption spectrophotometer. Meanwhile, K and Na were measured using a flame photometer. The mineralogy was assessed by X-ray diffraction (XRD) analysis.

**Characteristics of K adsorption**

Soil K removal was carried out according to the method described by Beckett (1964) with some modifications. For each soil sample, three g of air-dried sample was put into a centrifuge tube, then 30 mL of KCl solution with different concentrations (0-200 mg L$^{-1}$) was added and the background electrolyte was 0.01 mol L$^{-1}$ CaCl$_2$. After that, it was shaken for one hour and allowed to stand for 24 hours. After equilibration time, the suspensions were filtered through filter papers. Next, the filtrate was analyzed for K with a flame photometer. The amount of K adsorbed by the soil is calculated from the difference between the amount of K added and the amount of K present in the equilibrium solution through the following equation:

$$q_e = (C_i - C_e) \times V/M \quad \text{..................(1)}$$

where $q_e$ is the amount K adsorbed by the solid phase of soil; $C_i$ and $C_e$ are the initial and equilibrium K concentrations in solution, respectively; V and M are the solution volume and mass of the soil used.

The data from the K adsorption experiment were simulated using the Freundlich equation in linear form. The Freundlich model is one of the most frequently used and earliest models to explain equilibrium adsorption (Febrianto et al., 2009). The Freundlich equation is written as follows:

$$q_e = K_f C_e^{1/n} \quad \text{.................................(2)}$$

The equation is converted into a linear form as follows

$$\log q_e = \log K_f + \frac{1}{n} \log C_e \quad \text{..................(3)}$$

where $q_e$ is adsorbed K (mg kg$^{-1}$), $C_e$ is concentration of K in the equilibrium solution (mg L$^{-1}$), $K_f$ is adsorption capacity, $n$ is constant. The values of $1/n$ and $K_f$ are obtained from the slope and intercept of the relationship graph $q_e$ (Y axis) with $K_f$ (X axis), respectively. $1/n$ and $K_f$ were defined as buffering of K sorption and K sorption capacity, respectively.

**Data analysis and interpretation**

Soil characteristic data is processed first using Microsoft Excel. The chemical properties of the soil were interpreted as referring to the criteria for assessing the soil's chemical properties (Eviati and Sulaeman, 2009) and describing the soil K adsorption.

**Results and Discussion**

**Soil characteristics at the study site**

Based on the criteria of Eviati and Sulaeman (2009), all soils studied had clay texture. The soil reaction was
slightly acidic to slightly alkaline, with base saturation (BS) status was high to very high. Soil organic C was very low to low, and soil potential K was very high. Soil exchangeable Ca was very high, and exchangeable Mg and K were high to very high. The CEC of all soils were very high (Table 2). Based on the Soil Map with a scale of 1:50,000, Brebes Regency (ICALRD, 2017), the soils studied were derived from the parent material of clay sediment to limestone. The soil developed from clay sediment and limestone had a clay soil texture. Limestone contains minerals CaMg(CO$_3$)$_2$, which is high, and its weathering produces Ca$^{2+}$, Mg$^{2+}$, and CO$_3^{2-}$. This condition causes high exchangeable Ca and Mg in the soil, so BS was also high. Furthermore, the presence of CaMg(CO$_3$)$_2$ increased soil pH. As for Al cations precipitated so that exchangeable Al decreased. The studied soils are located in the tropics, with an average rainfall of about 2,000 mm yr$^{-1}$ in 2021 (BPS Kabupaten Brebes, 2022). The high annual rainfall and the high average temperature in the tropics caused the level of weathering of organic matter in this area to be high so that the turnover of organic matter in the soil is relatively short, and as a result, the organic C of the soil is very low to low. The potential K of the soil is influenced by the parent material, which is also closely related to the level of soil management. Soils in shallot cultivation areas in Central Java (especially in the locations studied) generally had a relatively high level of land use intensification. As a result, residual K in the soil from fertilization or K from irrigation water is still stored in the soil. Furthermore, soil K sources could also come from minerals containing K (e.g., mica).

Table 2. Soil characteristics at the study site.

<table>
<thead>
<tr>
<th>Soil Characteristics</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B6</th>
<th>B7</th>
<th>B8</th>
<th>B9</th>
<th>B10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (%)</td>
<td>67.1</td>
<td>73.0</td>
<td>70.8</td>
<td>74.9</td>
<td>58.2</td>
<td>73.0</td>
<td>47.7</td>
<td>63.3</td>
<td>45.6</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>5.40</td>
<td>1.14</td>
<td>1.36</td>
<td>2.55</td>
<td>4.98</td>
<td>1.71</td>
<td>11.9</td>
<td>4.50</td>
<td>16.8</td>
</tr>
<tr>
<td>pH H$_2$O</td>
<td>5.93</td>
<td>7.30</td>
<td>6.88</td>
<td>6.80</td>
<td>7.24</td>
<td>6.56</td>
<td>6.87</td>
<td>6.56</td>
<td>6.95</td>
</tr>
<tr>
<td>EC (µS cm$^{-1}$)</td>
<td>859</td>
<td>484</td>
<td>1,253</td>
<td>1,015</td>
<td>1,934</td>
<td>589</td>
<td>1,547</td>
<td>460</td>
<td>1,004</td>
</tr>
<tr>
<td>Organic C (%)</td>
<td>1.21</td>
<td>2.19</td>
<td>0.73</td>
<td>0.82</td>
<td>0.58</td>
<td>0.72</td>
<td>0.88</td>
<td>0.81</td>
<td>0.95</td>
</tr>
<tr>
<td>Potential K (ppm K)</td>
<td>1,151</td>
<td>982</td>
<td>946</td>
<td>1,172</td>
<td>803</td>
<td>1,331</td>
<td>936</td>
<td>1,081</td>
<td>590</td>
</tr>
<tr>
<td>Exchangeable cations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ca (cmolc kg$^{-1}$)</td>
<td>43.0</td>
<td>65.0</td>
<td>54.2</td>
<td>32.3</td>
<td>33.5</td>
<td>37.2</td>
<td>34.6</td>
<td>35.4</td>
<td>46.1</td>
</tr>
<tr>
<td>Mg (cmolc kg$^{-1}$)</td>
<td>9.37</td>
<td>7.32</td>
<td>9.68</td>
<td>9.49</td>
<td>7.46</td>
<td>9.34</td>
<td>6.84</td>
<td>7.07</td>
<td>7.51</td>
</tr>
<tr>
<td>K (cmolc kg$^{-1}$)</td>
<td>1.16</td>
<td>2.03</td>
<td>1.51</td>
<td>1.60</td>
<td>1.16</td>
<td>1.73</td>
<td>0.76</td>
<td>0.82</td>
<td>0.76</td>
</tr>
<tr>
<td>CEC (cmolc kg$^{-1}$)</td>
<td>71.6</td>
<td>81.9</td>
<td>81.4</td>
<td>60.3</td>
<td>55.3</td>
<td>66.0</td>
<td>53.1</td>
<td>56.5</td>
<td>67.2</td>
</tr>
<tr>
<td>BS (%)</td>
<td>75.6</td>
<td>94.4</td>
<td>84.2</td>
<td>79.0</td>
<td>79.0</td>
<td>81.5</td>
<td>81.1</td>
<td>78.2</td>
<td>82.1</td>
</tr>
<tr>
<td>Acidity:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Exchangeable Al (cmolc kg$^{-1}$)</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Exchangeable H (cmolc kg$^{-1}$)</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
</tbody>
</table>

tr = immeasurable.

Based on the soil analysis results (Table 2), the soil pH at the study site was classified as slightly acidic to slightly alkaline. The pH values of this soil were relatively high compared to the pH of upland soils in Indonesia. It is thought to be primarily the result of the dominant anaerobic condition of the soil, which is often flooded (paddy fields), which can increase soil pH. Anaerobic conditions in this soil were supported by soil conditions, which are primarily clayey in texture, producing a massive soil structure.

The soil's electrical conductivity (EC) at the study site was classified as very low, recommending that the soils studied were not saline. This condition was probably due to the leaching or dilution of salts by rain water. The organic C content at the dominant study site was classified as very low, possibly due to the intensive farming system, which was carried out intensively without returning back the biomass from plant residues to the soil or without the application of animal manure and other organic fertilizers.

Based on the soil analysis results (Table 2), the value of the CEC of the soil at the study site, according to the assessment criteria used, was classified as very high. One of the reasons for the high CEC of the soil at the study site was the high clay content and the presence of 2:1 mineral clay in the soil. The clay content influenced high CEC due to the contribution to the amount of negative charge in soils. Therefore, with a high negative charge, soils dominated by the clay fraction have high aggregate stability due to strong bonding among soil particles. Soils with clay texture and high organic matter have a higher CEC than sandy soils with low organic matter (Havlin et al., 2014). The value of BS at the research sites observed was classified as high to very high criteria. High base saturation means the availability of sufficient base cations for plant needs in terms of soil nutrients. The maximum amount of cations that the soil can absorb indicates the value of the soil's cation exchange capacity.

**Characteristics of soil potassium adsorption**

The water-soluble K, exchangeable K, and potential K were 6.68 ppm, 427 ppm, and 893 ppm, respectively.
(Figure 1). The parent material of the soil influences K levels in the soil. Inceptisols are derived from clay deposits to calcareous sandstone and marl (ICALRD, 2017). The proportion of K form from low to high in the soil studied has the order, namely: water-soluble K < exchangeable K < potential K. The water-soluble K ranges 0.50%, exchangeable K 32.2%, and potential K 67.3%. It can be assumed that most of the K in the soil was high, but the water-soluble K is very low. The research results reported by He and Chen (2013) showed that the amount of K ions retained in the solid phase of the soil is much more significant than that dissolved in the soil solution. The soil at the research location is dominated by 2:1 clay minerals, namely vermiculite, HIV (hydroxy-interlayer vermiculite), and Smectite (Table 3).

Soils with a high content of 2:1 clay minerals contain more non-exchangeable K than kaolinite and other silicate clay minerals. This can be clarified by analyzing the K adsorption of the soil.

K adsorption determination in this study used the Freundlich equation. The Freundlich isotherm equation provides a closer description of the natural adsorption phenomenon in the soil (Kenyanya et al., 2014). The Freundlich equation model assumes that there is more than one surface layer (multilayer) and the sides are heterogeneous; that is, there is a difference in binding energy on each side or a better correlation with a mixture of clay minerals (Hannan et al., 2007; Fuentes et al., 2014). The parameters of the Freundlich equation were determined using the linear form of the Freundlich equation. The Freundlich curve of K adsorption by the soils is presented in Figure 2. Most curves showed that K was continuously adsorbed by the soils, indicating that the soil had a high capability to sorb K.

Figure 3 shows the linear form of the Freundlich equation. The values of $R^2$ ranged from 0.908 to 0.9839. The values of $R^2$ showed that the linear equations were valid to determine the Freundlich parameters, namely the constant $K_f$ and n. The constant $K_f$ was defined as K sorption capacity index and 1/n was defined as buffering capacity. The constant $K_f$ and 1/n values are presented in Table 3.

Table 3 shows that $K_f$ and 1/n values of K sorption varied among the soils. A low $K_f$ value indicated that most of the K ions are in the soil solution system and are available for transport and chemical processes in the soil and absorbed by plants. High value of $K_f$ indicated that K was sorbed by the soil particle (Al-Zubaidi et al., 2008).

The soil at the study site produced $K_f$ values ranging from 0.10 (location B7) to 46.6 (location B10) (Table 3). The value of $K_f$ at B10 is higher compared to soils in other locations, thus indicating a higher adsorption capacity. Soils with $K_f$ values <3.49 indicated that their soil K was higher in soil solution compared to high soils with $K_f$ > 3.49 (Kenyanya et al., 2013). The 1/n value obtained from the Freundlich isotherm describes the K sorption buffering capacity. A measure of the heterogeneity of a system, namely a more homogeneous system, will have a 1/n value close to one. A more heterogeneous system will have a 1/n value close to zero (Hussain et al., 2006). Soil with low buffering capacity requires lower fertilization. 1/n value >1 indicates K adsorption on the soil surface relatively fast. The higher the 1/n value, the faster the adsorption reaction. K buffering capacities at the study site had a value 1/n >1, indicating that K sorption in the soil studied in Brebes was relatively fast.

At the shallot area in Pagejugan Village, Brebes district (B10) had a higher adsorption capacity and lower buffering capacity than the soil in other locations. It indicated that even slow in K sorption but the ability to sorb K was high. It could be related to the soil clay mineral type in B10 sample.
Figure 2. Adsorption isotherms of K by Freundlich.
Figure 3. The linear form Freundlich equation of the K sorbed.
The management of K in the soils at the study site needs good K management, including the application of organic matter, biofertilizer, or K-solubilizing bacteria to increase the bioavailability of K. The results of Misskire et al. (2019) showed that the application of K to intensively cultivated lands in North Western Ethiopia, East Gojjam zone, with the Freundlich model, showed $K_f$ values mostly < 3.44 and $1/n$ values ranging from 1.09 to 1.55. The illite-smectite clay mineral dominates the soil at this location. Compared to the study by Misskire et al. (2019), the $K_f$ values in the soil at the study sites (B2, B4, B6, B8, B9, and B10) were relatively higher. Thus the K adsorption capacity of the soil in the shallot area is relatively high, which is also indicated by the high potential K (Table 2 and Figure 1). The difference in the adsorption capacity of the soils at the study sites is related to the clay mineral type, the clay mineral's surface properties, and other related factors. Therefore, the soil at the study site needs good K management, including the application of organic matter, biofertilizer, or K-solubilizing bacteria to increase the availability of K.

Table 3. Parameters of adsorption and types of clay minerals at the study site.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Linear Equations</th>
<th>$K_f$</th>
<th>$1/n$</th>
<th>$R^2$</th>
<th>Clay Mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y = 1.59x + 0.0609</td>
<td>1.15</td>
<td>1.59</td>
<td>0.9080</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Y = 1.237x + 0.6897</td>
<td>4.89</td>
<td>1.24</td>
<td>0.9630</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Y = 1.8663x - 0.4452</td>
<td>0.36</td>
<td>1.87</td>
<td>0.9142</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Y = 1.0038x + 1.0041</td>
<td>10.09</td>
<td>1.00</td>
<td>0.9757</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>Y = 1.3402x + 0.5425</td>
<td>3.49</td>
<td>1.34</td>
<td>0.9725</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Y = 2.2414x - 0.9796</td>
<td>0.10</td>
<td>2.24</td>
<td>0.9839</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Y = 1.278x + 0.6113</td>
<td>4.09</td>
<td>1.28</td>
<td>0.9631</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Y = 1.0878x + 0.9775</td>
<td>9.50</td>
<td>1.09</td>
<td>0.9547</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Y = 0.8232x + 1.6679</td>
<td>46.6</td>
<td>0.82</td>
<td>0.9252</td>
<td>++</td>
</tr>
</tbody>
</table>

+++ = dominant phase (>50%); ++ = major phase (20–50%); + = minor phase (5–20%); *hydroxy-interlayer vermiculite.

Management of K in the soils at the study site

The results of the analysis of K adsorption using the Freundlich equation showed that most of the soil in the study area has a relatively high ability to adsorb K (Figure 2 and Table 3), which is also supported by high potential K (Table 2) and is dominated by the clay minerals vermiculite and HIV (Table 3). In addition, these soils have characteristics such as clay texture, slightly acid to slightly alkaline soil reaction, low organic C, high-very high CEC, and BS (Table 2). The efficiency of K fertilization needs to be increased through various efforts to increase the availability of K for plants. In addition, it is also necessary to maintain the equilibrium concentration of exchangeable K, Ca, and Mg in the soil to avoid competition between these ions to be absorbed by plants and to ensure K, Ca, and Mg nutrients are in sufficient condition to supply plant needs.

The available form of K is only about 32.68% of the total K found in the soil (Figure 1). These conditions indicate that there is a huge opportunity to harvest soil K, which is around 67.3% of the total soil K. If this opportunity can be exploited, some of the K needs of plants can be supplied from the soil so that fertilization becomes efficient. Soil status K significantly affects fresh bulb weight per plant and dry bulb weight per plant. The higher the status K of the soil, the higher the weight yield of fresh and dry bulbs per plant (Sumarni et al., 2013). The research results by Muliana et al. (2018a) showed that K fertilization was only significantly correlated with shallot production during the rainy season. The correlation between K fertilization rate and fresh bulb yield was positive. Lower bulb yields are more likely when farmers apply less than 125 kg ha$^{-1}$ of K fertilizer. However, there was no clear relationship between the use of K fertilizer and bulb yield. The unclear relationship may be due to the high concentration of exchangeable K$^+$ (Sopha, 2022). Increasing fertilizer beyond the recommended level had no positive effect on shallot growth or yield but
increased adsorbed K, soil EC, loss of organic matter, and NO\textsubscript{3}-N in the soil (Lee et al., 2012).

There are better strategies than over-fertilization to increase soil K because soil K will undergo further adsorption with the presence of 2:1 type clay minerals. Therefore, managing the K available pool is a better strategy for K management in the soil by liberating the Fixed K in the interlayer 2:1 type (Linquist et al., 2022). The high residue of nutrients, especially K, requires other efforts to increase the efficiency of using nutrients that are already in the soil, such as by adding organic fertilizers or biological fertilizers, or ameliorant so that the nutrients that have accumulated in the soil can be optimally absorbed by plants and can reduce pollution environment. Therefore, recommendations for K fertilization for such high fixation soils or where much of the added K has been adsorbed should be based on adsorption isotherms rather than soil tests alone. Field studies with ameliorants, such as biofertilizers or biological, must update the adsorption characteristics to verify the experimental results.

Various studies have shown that organic acid exudate is very important in increasing soil K availability. Soil microorganisms can release various types of organic acids to dissolve insoluble K into available forms of K that plants easily absorb. Sheng and He (2006) reported that the production of organic acids such as oxalic acid and tartaric acid, gluconic acid and 2-keto gluconic acid, citric acid, malic acid, and succinic acid caused the dissolving of illite and feldspar by microorganisms. Some research results show that tartaric acid appears to be the most abundant K mineral dissolving agent (Keshavarz Zarjani et al., 2013). In this case, the microorganism that plays a role in dissolving K is the K solubilizing bacteria.

Some bacteria that can dissolve potassium in the soil include Bacillus sp., Paenibacillus sp., and B. edaphicus (Sheng, 2005; Liu et al., 2012). In addition, several studies have reported the beneficial effect of PGPR (plant growth-promoting rhizobacteria) on shallot growth and production (Yeptho et al., 2012; Čolo et al., 2014). However, the effect of PGPR varies from location to location and from year to year. This phenomenon is because the inoculated bacteria compete with native soil microbiota, whose adaptability is often better (Čolo et al., 2014; Bishnoi, 2015). In order to achieve the maximum beneficial effect of these rhizobacteria, the proper PGPR strain must be selected in each soil-plant system (Ruzzi and Aroca, 2015).

**Conclusion**

The soil characteristics at the studied location are clayey textured, and the soil reaction was slightly acidic to slightly alkaline. BS was high to very high status. Soil organic C was very low to low status and soil potential K was very high status. Furthermore, exchangeable Ca, Mg, K, and CEC were very high status. The proportion of K form from low to high in the soil studied has the order: water-soluble K $<$ exchangeable K $<$ potential K. Based on the results of K adsorption from the Freundlich equation, it shows that the K adsorption capacity of the soil in the shallot area was relatively high. Therefore, to increase the efficiency of K fertilizer, soil microorganisms, especially bacteria capable of dissolving K, which can produce high organic acid exudates, can be developed in soils dominated by clay mineral 2:1. Thus, to verify the experimental results, field studies with ameliorant such as biofertilizer or biological are needed to update the adsorption characteristics.

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**References**


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