

QUANTITY-INTENSITY RELATIONSHIP OF SOIL POTASSIUM OBSERVED IN A SHALLOT PRODUCTION CENTER, CENTRAL JAVA, INDONESIA

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ABSTRACT

This study examined the availability of soil potassium (K) in the shallot specialty agriculture in Brebes Regency, Indonesia from 2022 to 2023 through the relationship of quantity-intensity (Q/I). The research site primarily consisted of clay textured soils with medium to high exchangeable K (Ex-K). The non-exchangeable K was relatively high. The results showed that the K equilibrium activity ratio (ARe^K) varied with the mean K in edge-positioned 2:1 clay minerals. High Ex-K does not necessarily reflect high K activity. A greater negative of labile K (ΔK^0) at the study site indicates a better K release into the soil solution. The average potential buffering capacity (PBC^K) was relatively high at low K saturation. This suggested that the soil can efficiently release K into the soil solution when the K level in the soil solution decreases, either for plant uptake or leaching. The average free energy of K (ΔG) appeared to be sufficient for plants. This research emphasized the importance of Q/I evaluation to better understand the characteristics and behavior of soil potassium, with the presence of specific clay minerals. The outcome of the research indicated the necessity of re-examination of current K fertilization scheme to improve the efficiency of K fertilization.

Key words: clay mineral, exchangeable K, labile K, potassium buffering capacity

INTRODUCTION

Shallots (*Allium cepa* L.) are one of essential food produces in the world, including Indonesia. Based on the Indonesian Statistics (Badan Pusat Statistik 2022), this commodity has been planted throughout the country, either in hilly areas or in lowlands. Nonetheless, only a few successful production centers exist, notably Brebes regency, contributing more than 2 M tons in 2021, which was around 60% at provincial level or about 17% to total national accounts. The productivity, nonetheless, fluctuates around 10 tons/ha. This warrants the necessity for an in-depth study for soil nutrient evaluations allowing optimization of nutrients for plants while avoiding perilous environmental impacts.

Bulbs, like shallots, tend to require more K than other horticulture plants (Bekele 2018; Sumiati and Gunawan 2007). Farmers tend to add more K to soil whenever bulbs are planted, without any knowledge of the K levels in soil. In Brebes, for instance, applications ranged from 22 to 213 kg/ha

K₂O (Muliana et al. 2018). Based on field observations at the research site in Brebes Regency, most of the fertilizer's shallot farmers use to provide K nutrients are KCl, Kamas, and/or NPK Phonska. The average application of these K fertilizers was approximately 150 kg/ha K₂O. However, the recommended K fertilizer dosage based on the nutrient needs of shallot plants in the soils of Brebes Regency is 90 kg/ha K₂O (Balai Penelitian Tanah 2021). These practices result in elevated levels of soil K residue and low levels of soil organic carbon in shallot cultivation areas. K residues in the soil generally increase with higher soil K status and dosage of K fertilizer applied (Sumarni et al. 2012). The 25% HCl-extractable K levels in soils from Central Java (Tegal and Brebes) ranged from 26 to 49 mg/100 g K₂O, which falls under the moderate to high criteria. The 25% HCl-extractable K levels in soils from several shallot-growing areas in Brebes Regency range from 30 to 66 mg/100 g K₂O, with an average of 55 mg/100 g K₂O, categorized as high (Muliana et al. 2018). These K dynamics are particularly significant in tropical soils, where the interactions between K and soil chemical and physical properties tend to be more complex (Volf et al. 2021).

Potassium in soil continually shifts chemical equilibrium of its three forms: water-soluble, exchangeable, and non-exchangeable (Huang 2005). Replenishing K in the solution and exchanging it from the non-exchangeable pool are both impacted by the presence of 2:1 clay minerals (Oumar et al. 2022), which are common in clay-textured soils. Conventional availability assessment of soil K typically focuses only on water-soluble and exchangeable K. One widely used method for measuring exchangeable K is ammonium acetate extraction (1 M NH₄OAc, pH 7), which has been proven reliable for many types of soil. However, this technique is rather inadequate for soils containing illite, vermiculite, or intensively cultivated soils (Islam et al. 2017; Jalali 2007; Khan et al. 2014; Moody and Bell 2006; Zarrabi and Jalali 2007).

Beckett (1964) quantity-intensity (Q/I) relationship offers a more thorough insight into K behaviour in soil, especially in intensively cultivated tropical areas (Shil et al. 2021). Q/I analysis enables the calculation of key parameters, including the equilibrium activity ratio of K (ARe^K), labile K (ΔK^0), and the potential buffering capacity of K (PBC^K). These factors are crucial for assessing soil K availability and retention ability (Saleque et al. 2009; Zhang et al. 2011). ARe^K is a measure of the availability or intensity of soil K, which increases with swelling concentrations of K. Elevated labile K indicates an escalated release of K into the soil solution due to a greater reserve of soil K. This increase in K release can be observed by comparing labile K and K extracted with NH₄OAc. If the K extracted with NH₄OAc is lower than ΔK^0 , K is released into the soil solution (Sparks and Huang 1985). The Release Threshold Concentration (RTC) values can also determine the K release threshold. Datta and Sastry (1988) research revealed that the RTC values for representative Inceptisol, Alfisol, and Vertisol were 2.2, 1.6, and 1.0 mg/L, respectively. If the K concentration in the soil solution is below the RTC value, K is strongly bound to soil particles and unavailable to plants. PBC^K is the capacity of the soil to maintain K levels in the soil solution when K is added, leached, or absorbed by plants. In soils with low PBC^K, added K is easily leached out. Meanwhile, K fertilizer applied into soils with high PBC^K could be preserved for the next cropping season (Lumbanraja et al. 2020). High PBC^K levels suggest sufficient availability of K in soils, while low PBC^K levels indicate a necessity for K fertilization (Al-Jumaily et al. 2022). As K activity increases, PBC^K reduces as the soil reaches saturation; hence, diminishing the uptake from fertilizers. These parameters are particularly relevant for managing K in tropical clay soils, where a high clay content may influence K retention and release dynamics (Hamand et al. 1999).

The importance of the Q/I relationship in tropical soils has been highlighted in several studies. Sharma et al. (2012) and Shil et al. (2021) emphasize the roles of soil texture, organic matter, and pH in influencing K availability, with Shil et al. (2021) recommending detailed Q/I assessments to optimize K management. Non-exchangeable K is vital in K-depleted soils (Bilias and Barbayiannis 2018). Soil texture and plant demand are key drivers of K dynamics (Rosolem and Steiner 2017). Additionally, proper K management enhances onion yields through improved photosynthesis and nutrient translocation (Hasan 2019). Straw-returning practices improve the Q/I curve by strengthening the soil

organic matter and K balance, reducing the need for synthetic fertilizers (Zhang et al. 2021; Zhu et al. 2020).

The Q/I approach is particularly relevant in tropical clay soils because of the complex interplay between soil texture and mineral composition. Studies have shown that soils with high levels of calcium and magnesium tend to exhibit lower ARE^K levels, which complicates K management (Beckett 1964). Additionally, kaolinitic soils, common in tropical regions, often exhibit unique K dynamics influenced by interactions with elements such as calcium and magnesium (Volf et al. 2021). These dynamics are crucial for understanding the long-term sustainability of K fertilization practices in tropical agricultural systems.

Managing K in tropical soils is critical for maintaining high yields, optimizing fertilization practices, and minimizing environmental impacts. Given the significance of K dynamics in tropical soils, particularly in regions with high-intensity shallot cultivation, this study sought to examine soil K availability using the Q/I approach. The goal is to enhance nutrient management strategies in clay soils under these cultivation conditions.

MATERIALS AND METHODS

Study site and soil sampling. Soil samples were taken from various points within the shallot production centers of Brebes Regency, Indonesia, one of the country’s largest shallot producers. Composite samples were taken at a depth of 0-30 cm, purposively collected from sixty-one locations, spanning from coastal lowlands in the north (about 4 m above sea level) to southern hilly regions, averaging around 1,076 m above sea level (Table 1). At each location, a composite soil sample was collected from to 5-8 subsample points selected to represent the location, resulting sixty-one soil samples. Coordinates of all sampling sites were recorded by using a navigation receiver. Additional height data of each site was retrieved from DEMNAS data (<https://tanahair.indonesia.go.id/demnas/#/>).

Based on the 1:50,000 scale Soil Map of Central Java Province (ICALRD 2017), soils in the research area are originated from clay deposits, as well as calcareous sandstone and napal (Inceptisols) and calcareous sandstone and napal (Alfisols). With this sense, weathering processes induce soil materials with a clay texture. Andisols in the study area were developed from andesite tuff.

Table 1. Soil order, soil textural class and location of studied sites

Sample Code	Coordinates		District Name	Soil Order*	Soil Textural Class
	Latitude	Longitude			
B-1	-6,891380	109,043850	Brebes	Inceptisols	Clay
B-2	-6,878920	109,027790	Wanasari	Inceptisols	Clay
B-3	-6,901080	109,019650	Wanasari	Inceptisols	Clay
B-4	-6,861640	109,016660	Wanasari	Inceptisols	Clay
B-5	-6,852280	109,017380	Wanasari	Inceptisols	Clay
B-6	-6,862940	109,008430	Wanasari	Inceptisols	Clay
B-7	-6,879470	109,005370	Wanasari	Inceptisols	Clay
B-8	-6,873920	108,994330	Bulakamba	Inceptisols	Silty clay
B-9	-6,922835	108,972413	Bulakamba	Inceptisols	Clay

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Sample Code	Coordinates		District Name	Soil Order*	Soil Textural Class
	Latitude	Longitude			
B-10	-6,843370	109,051010	Brebes	Inceptisols	Clay
B-11	-6,849360	109,011580	Wanasari	Inceptisols	Silty clay
B-12	-6,903880	108,987960	Bulakamba	Inceptisols	Clay
B-13	-6,970733	108,799153	Banjarharjo	Inceptisols	Clay
B-14	-6,977494	108,787706	Banjarharjo	Inceptisols	Clay
B-15	-6,981628	108,812131	Banjarharjo	Inceptisols	Clay
B-16	-6,997622	108,845275	Banjarharjo	Alfisols	Clayey loam
B-17	-6,994344	108,835981	Banjarharjo	Inceptisols	Clay
B-18	-6,981875	108,824697	Banjarharjo	Alfisols	Clay
B-19	-6,989839	108,786881	Banjarharjo	Alfisols	Clay
B-20	-6,910390	109,068850	Brebes	Inceptisols	Clay
B-21	-6,943370	109,042390	Jatibarang	Inceptisols	Clay
B-22	-6,960340	109,016630	Songgom	Inceptisols	Silty clay
B-23	-7,062631	108,883798	Ketanggungan	Inceptisols	Clay
B-24	-7,071930	108,887260	Ketanggungan	Alfisols	Clay
B-25	-7,108083	108,879528	Ketanggungan	Inceptisols	Silty clay loam
BR-4	-7,032355	108,937427	Larangan	Inceptisols	Clay
BR-13	-7,019022	108,884299	Ketanggungan	Inceptisols	Clay
BR-14	-7,043762	108,875962	Ketanggungan	Inceptisols	Clay
BR-14-BM	-7,048029	108,877185	Ketanggungan	Inceptisols	Sandy loam
BR-15	-6,998135	108,949331	Larangan	Inceptisols	Clay
BR-18	-7,081967	108,813576	Banjarharjo	Inceptisols	Clayey loam
BR-19	-7,074378	108,823840	Banjarharjo	Inceptisols	Clay
BR-21	-6,953729	108,773517	Banjarharjo	Inceptisols	Clay
BR-26	-7,059159	108,832898	Banjarharjo	Inceptisols	Clay
BR-28	-7,048649	108,920629	Larangan	Inceptisols	Silty clay
BR-34	-7,074262	108,905202	Larangan	Inceptisols	Clay
BR-42	-7,262519	109,076535	Paguyangan	Andisols	Sandy loam
BR-43	-7,278700	109,080274	Paguyangan	Inceptisols	Loam
BR-45	-7,215079	109,048610	Sirampog	Inceptisols	Silty clay loam
BR-46	-7,250005	109,035834	Paguyangan	Inceptisols	Clay
BR-47	-7,186697	109,013154	Tonjong	Inceptisols	Clay

Sample Code	Coordinates		District Name	Soil Order*	Soil Textural Class
	Latitude	Longitude			
BR-48	-7,024072	109,004307	Songgom	Inceptisols	Clay
BR-50	-7,227892	109,033250	Bumiayu	Inceptisols	Silty clay
BR-51	-7,286002	109,050550	Paguyangan	Inceptisols	Loam
BR-54	-6,910649	109,025848	Wanasari	Inceptisols	Clay
BR-55	-6,978900	109,064536	Jatibarang	Inceptisols	Clay
BR-56	-6,945365	108,959854	Larangan	Inceptisols	Clay
BR-57	-6,918389	108,823238	Tanjung	Inceptisols	Clay
BR-58	-6,927355	108,777129	Losari	Inceptisols	Clay
BR-59	-6,969079	108,777574	Banjarharjo	Inceptisols	Clay
BR-60	-6,957134	108,810483	Banjarharjo	Inceptisols	Clay
BR-61	-6,964073	108,839778	Banjarharjo	Inceptisols	Clay
BR-62	-7,002359	108,840048	Banjarharjo	Alfisols	Clay
BR-63	-6,916726	108,861768	Kersana	Inceptisols	Clay
BR-64	-6,892315	108,864280	Tanjung	Inceptisols	Clay
BR-65	-6,959193	108,979308	Larangan	Inceptisols	Clay
BR-66	-6,906537	108,869498	Kersana	Inceptisols	Clay
BR-67	-6,866896	108,988719	Wanasari	Inceptisols	Clay
BR-68	-6,841399	109,022253	Brebes	Inceptisols	Silty clay
BR-69	-6,852660	109,049987	Brebes	Inceptisols	Clay
BR-70	-6,863630	109,059646	Brebes	Inceptisols	Clay

*Soil Map of Brebes Regency 1:50,000 (ICALRD 2017)

Soil physicochemical analyses. Soil characteristics were analyzed in a soil laboratory of the Department of Soil Science and Land Resources, Faculty of Agriculture, Bogor Agricultural University. Composition of clay minerals was examined at the Soil Research Institute, Bogor, and the tekMIRA Mineral and Coal Testing Center. Initially, soil samples were air-dried, and then pounded and sifted through <2 mm and 2 mm sieves for the analysis of soil characteristics (including some soil chemical properties and texture). Analysis of soil mineral analysis was carried out using $\pm 74\mu\text{m}$ or 200 mesh. Soil chemical properties were measured in the laboratory, including pH H₂O (1:5) (SNI 03-6787-2002), organic C (Walkley and Black) (Nelson and Sommers 1996; Tan 1996), Cation Exchange Capacity/CEC (NH₄OAc pH 7) (Sumner and Miller 1996), exchangeable K and Na determined by flame photometry, exchangeable Ca and Mg determined by atomic absorption spectrophotometry (AAS) (Helmke and Sparks 1996; Suarez 1996), and three-fractional soil texture (sand, silt, clay) using the pipette method (Pansu and Gautheyrou 2006; Tan 1996). Composition of clay minerals was analyzed using X-ray diffractometry (XRD).

The determined soil K shapes included: water-soluble K/water-K (soil and water ratio 1:5) then shaken for 5 min; exchangeable K (Ex-K) was extracted with NH₄OAc (buffered by pH 7, 1 mol/L, 20 ml), stirred evenly and left for approximately one night, stirred again, centrifuged for 10 min, and

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decanted; K extracted with HNO₃ was carried out by soil heating (<2 mm, 2.5 g) with HNO₃ (1 mol/L, 25 mL) for 15 min (Pratt 1965). Extracted K was analyzed using a flame photometer. Available K (Avail K) is defined as the sum of water-K and Ex-K, whereas non-exchangeable K (NE-K) is defined as K extracted with HNO₃ subtracted by Avail K. The percentage K saturation (K Sat) was determined using the following equation:

$$\% \text{ K saturation} = \frac{\text{Exchangeable K} \times 100\%}{\text{CEC}}$$

Q/I K parameters. Beckett method (Beckett 1964) used to observe potassium Q/I parameters as illustrated in Fig. 1. Each soil sample was taken as much as 3 g and placed in a centrifuge tube. A 15 ml 0.02 M CaCl₂ solution was inserted, then KCl was added with a concentration of 200 mg/L K and aquadest until a volume of 30 ml so that the concentration of the K solution series becomes 0.00; 6.67; 13.33; 20.00; 33.33; 46.67; 66.67; 80.00; and 100.00 mg/L. Tubes were then shaken for 60 min and allowed to sit for 18-hours to achieve balance. After the resting period, prior filtered, Electrical Conductivity (EC) of the soil sample was measured, and then the supernatant solution was collected. Afterward, the filtrate was examined using a flame photometer, and for Ca and Mg using AAS. The change in K in soil solution was calculated using the following equation:

$$\Delta K = (CK_i - CK_f)$$

Variance between the initial concentration, introduced as KCl (CK_i), and the concentration of K in the soil solution after reaching equilibrium (CK_f), is represented by ΔK. A positive ΔK value signifies adsorption of K in soil solid phase, whereas a negative ΔK value indicates the release of K from soil solid phase into soil solution.

The ratio of K activity (AR^K) reflects the level of K intensity in soil solution, accounting for the presence of Ca and Mg, as follows:

$$AR^K = \alpha K / (\alpha Ca + Mg)^{1/2}$$

The ratio of K activity to Calcium (Ca) and Magnesium (Mg) activities after reaching equilibrium is referred to as AR^K, which is expressed in moles per liter (mol/L)^{1/2}. Additionally, activities of Ca and Mg are represented by αCa + Mg, while K activity is represented by αK, both of which are also expressed in moles per liter (mol/L).

Ion activity is calculated by this equation:

$$\alpha = \gamma M$$

where M = ion concentration (mol/L) and γ = ion activity coefficient.

The coefficient of ionic activity is obtained from Davies' equation (Davies 1962 *in* Ajiboye et al. 2015) with the following equation:

$$\log \gamma = -Az_i^2 \left[\frac{I^{1/2}}{1 + I^{1/2}} - 0.3I \right]$$

where A = constant (A = 0.511 at 25 °C); z_i = ion valence, and I = ionic strength. I (mol/L) is determined using the equation suggested by Griffin and Jurinak (1973):

$$I = 0.0129 \text{ EC}$$

The Q/I K relationship shows the quantity factor/ ΔK on the Y-axis and the intensity factor/ AR^K on the X-axis. The Q/I isotherm parameters include the activity ratio at equilibrium (AR^{eK}), which represents the AR^K value when ΔK is zero. Labile K (ΔK⁰) is obtained from the Q/I line intercept (K

on non-specific surfaces), while potential buffer capacity (PBC^K), which is an indicator of support capacity of soils, is estimated from the ΔK slope with ARe^K .

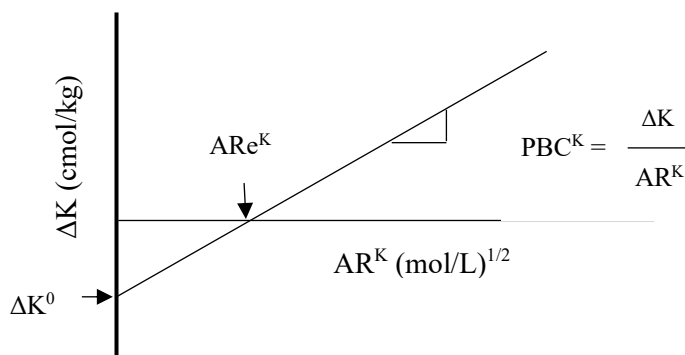


Figure 1. Theoretical Q/I of K in soils

The relationship between availability of K for plants and energy exchange of K with Ca in colloidal soil or the surface of plant roots is crucial (Woodruff 1955). In soils with neutral pH, Ca is typically the primary cation that can be exchanged. Free energy (ΔG) of K can be calculated using the equation proposed by Beckett (1972):

$$\Delta G = 2.303 RT \log ARe^K$$

The change in free energy (ΔG) is equal to the product of the gas constant (R), absolute temperature (T), and ratio of the activity of K in equilibrium (ARe^K), measured in kilojoules per mole (kJ/mol).

The Pearson correlation test (Gomez and Gomez 1984) was carried out to see the relationship between several soil chemical properties with water-soluble K, exchangeable K, non-exchangeable K, Q/I K parameters (ARe^K , PBC^K , ΔK^0) and ΔG .

RESULTS AND DISCUSSION

Soil characteristics of studied soils. Variations in soil properties taken at a depth of 0-30 cm are presented in Table 2. On average, soil pH was considerably neutral. Meanwhile, the level of organic C was fairly low, with remarkably high base saturation. These indicators suggested that a dissolved free base cation from parent material was also measured. The finding also revealed that soil exchangeable Ca was extremely high, while exchangeable Mg and K were high. Cation exchange capacity across all research locations was exceedingly high.

Table 2. Summary of physicochemical properties of soil (n = 61 samples)

Soil properties	Min - Max	Mean	Standard Error of Mean
Clay (%)	15.68 - 87.49	59.19	2.05
Sand (%)	1.07 - 61.91	11.50	1.65
Silt (%)	10.52 - 50.66	29.29	1.13
pH H ₂ O (1:5)	4.2 - 8.1	6.7	0.1
Organic C (%)	0.46 - 3.18	1.30	0.08
CEC (cmol/kg)	11.08 - 81.89	46.41	1.81
Exchangeable Ca (cmol/kg)	1.94 - 79.54	38.36	1.95

Soil properties	Min - Max	Mean	Standard Error of Mean
Exchangeable Mg (cmol/kg)	0.37 - 20.55	7.21	0.38
Exchangeable K (cmol/kg)	0.09 - 2.60	0.57	0.06
Exchangeable Na (cmol/kg)	0.06 - 5.48	0.89	0.15
Base Saturation (%)	22.27 - 100	100	4.92

Based on a soil map with a scale of 1:50,000, Brebes Regency (ICALRD 2017), the soils studied were derived from the parent material of clay deposits to calcareous sandstone and napal (Inceptisols), and calcareous sandstones and napal (Alfisols). Calcareous sandstone contains high minerals $\text{CaMg}(\text{CO}_3)_2$, and its weathering process yields Ca^{2+} , Mg^{2+} , and CO_3^{2-} . This initiated high exchangeable Ca and Mg, leading to high base saturation. The CO_3^{2-} ions undergo hydrolysis to produce OH^- ions so that soil pH increases. Consistently high annual temperatures in the tropics accelerate decomposition rate of organic matter, leading to a relatively short turnover of soil organic matter and resulting in low soil organic carbon (Hartono et al. 2023; Nursyamsi et al. 2007).

High soil CEC at the research site indicated a relatively neutral soil pH. This measure is influenced by clay content. Soils dominated by clay fractions have high cation exchange and water-holding capacities (Havlin et al. 2014). The 2:1 clay mineral is closely related to soil CEC, where the higher the 2:1 clay mineral content, the higher the CEC. Inceptisols in the research site having smectite and vermiculite had higher CEC than kaolinite or mixed clay minerals. This suggested that negative charge from permanent charge in 2:1 clay mineral significantly contributed to CEC. This charge originates from isomorphic substitution, producing an excess negative charge on Si tetrahedral and Al octahedral sheets.

Agricultural soils in the northern part of Brebes, including the Wanasari, Bulakamba, Jatibarang, Brebes, Ketanggungan, and Larangan districts, contain 2:1 clay mineral, including smectite, vermiculite, and HIV (Hydroxy-interlayer Vermiculite). Each observed soil sample also contained kaolinite and quartz (Table 3). Quartz minerals in clay fraction are primary minerals, which are resistant to alteration (Prasetyo et al. 2005). Synthetic K fertilizers, such as KCl, Kamas, and NPK fertilizers, are generally applied throughout planting seasons. Continual application of this fertilizer could lead to a considerable increase in the quantity of illite and vermiculite. This is primarily because of specific K fixation in the wedge zone, which arises from the interaction between clay minerals and the presence of K (Liu et al. 2008). NE-K and illite contents were significantly positively correlated (Samadi et al. 2008). These conditions illustrate that the K form of the soils comes mainly from the release of illite edges. Intensive agricultural management can elevate concentration of K, which causes Ex-K to decrease.

Forms of potassium in soils. This research found that concentration of water-soluble K ranged from 0.6 to 32.9 mg/kg, as shown in Table 4. Clayed soils, represented by B-5, B-12, BR-34, and BR-70, exhibited a higher concentration of water-soluble K than the others. These soils contained dominant mineral clays, *i.e.*, hydroxy-interlayer vermiculite (HIV), smectite, vermiculite, and quartz. These are abundantly found in soils over the northern part of the research site. This is possibly due to the fact that those agricultural fields are planted three times annually, where K fertilization has been a widespread practice. Research finding indicated that soils predominantly serve as a K-based cation exchange site (Table 4). As a result, excess K in cation-exchange complex can become water soluble. The correlation between water-soluble K and K saturation was found to be positive and significant ($r = 0.671^{**}$) (Table 5). This correlation implies that water-soluble K increases when cation exchange complex is saturated with K. Results also showed that clay-textured soils are quickly saturated with K.

Table 3. Semi-quantitative mineralogy of clay fractions

Sample code	Clay Fraction						
	Kaolinite	Halloysite	Illite	Smectite	Vermiculite	Quartz	Others
B-1	++						HIV +++
B-2	++				+++		
B-3	++				+++		
B-4	++						HIV +++
B-5	++						HIV +++
B-6	++				+++		
B-7	++				+++		
B-8	++				++		
B-9	++			+++			
B-10	++						HIV +++
B-11	++			++	+++		
B-12	++			++	++		
B-20	+			+	+++		
B-21	+			+			HIV +++
B-23	++			++	+++		
B-24	++			++	++		
BR-4	+		+	+		++	Cal +; Alb +; Mag tr
BR-13		++		++		+	Alb +; Cal tr; Rie tr
BR-14-BM		++		++		++	Alb +; Goe +; Mag tr
BR-15	+		+	+		++	Alb +; Mag tr; Cris tr

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Sample code	Clay Fraction						Others
	Kaolinite	Halloysite	Illite	Smectite	Vermiculite	Quartz	
BR-18		+	++	+		+	Alb ++; Mag+
BR-28	+			++		++	Alb +; Mag tr
BR-34			+	+		++	Cal++; Alb +; Mag tr
BR-42							Alb +++; Mag+
BR-46		++	++			Tr	Mag +; Alb +; Goe +
BR-47	+		+	Tr		++	Alb +; Mag tr
BR-56	+		++	++		++	Alb +; Mag tr
BR-57		+		++		++	Alb +; Cris tr
BR-63	+		+	++		++	Alb +; San +; Spha tr
BR-66	+			+		++	Alb +; Mag +; Cal tr
BR-68	+		+	+		++	Alb +; Mag tr

+++ = dominant phase (>50%); ++ = major phase (20–50%); + = minor phase (5–20%); and tr = <5%

HIV = hydroxy-interlayer vermiculite; Cal = Calcite; Alb = Albite; Mag = Magnetite; Rie = Riebeckite; Goe = Goethite; Cris = Cristobalite; San = Sanidine; Spha = Sphalerite

Table 4. Soil K content in various forms

Sample code	Water-K	Ex-K	NE-K	Avail K	K Sat
 (mg/kg)				(%)
B-1	4.7	203	344	207	0.73
B-2	6.0	289	307	295	0.90
B-3	6.1	328	309	334	1.03
B-4	3.6	234	445	238	0.99
B-5	32.9	1,014	338	1.047	5.25
B-6	4.5	238	450	242	1.10
B-7	8.2	449	366	457	1.74
B-8	3.3	160	379	163	0.77
B-9	5.2	176	321	181	0.80
B-10	1.5	90	280	91	0.34
B-11	5.9	265	421	271	1.40
B-12	26.9	636	622	663	3.01
B-13	2.2	94	336	96	0.44
B-14	2.3	164	396	166	0.83
B-15	3.0	160	329	163	0.91
B-16	1.9	90	115	92	0.40
B-17	3.1	129	350	132	0.87
B-18	2.2	133	347	135	0.70
B-19	4.4	222	436	227	0.99
B-20	8.8	246	398	254	1.05
B-21	4.0	148	149	152	0.68
B-22	1.8	86	203	88	0.36
B-23	2.8	133	256	135	0.70
B-24	7.3	101	182	109	0.51
B-25	3.0	101	227	104	0.60
BR-4	7.1	333	409	340	2.05
BR-13	0.6	54	165	55	0.25
BR-14	0.6	50	117	50	0.25
BR-14-BM	5.5	275	322	281	2.36
BR-15	4.1	236	386	240	1.31
BR-18	3.5	121	126	125	0.93
BR-19	6.4	258	238	265	1.44
BR-21	2.4	106	262	108	0.68
BR-26	1.2	57	166	58	0.26
BR-28	3.7	155	325	159	0.85

Quantity-intensity relationship of soil potassium.....

Sample code	Water-K	Ex-K	NE-K	Avail K	K Sat
 (mg/kg)				(%)
BR-34	13.5	910	108	924	4.77
BR-42	2.4	38	67	41	0.88
BR-43	4.6	452	30	456	5.25
BR-45	1.7	54	227	55	0.58
BR-46	1.3	305	14	307	3.71
BR-47	1.9	97	270	99	1.07
BR-48	2.8	142	284	145	0.95
BR-50	2.5	58	166	60	0.55
BR-51	0.9	60	124	61	0.59
BR-54	6.4	161	411	168	2.35
BR-55	5.0	140	274	145	1.18
BR-56	2.7	115	328	118	0.56
BR-57	3.3	160	352	163	1.00
BR-58	1.6	102	256	104	0.51
BR-59	3.4	210	213	214	1.44
BR-60	2.2	128	259	131	0.67
BR-61	3.6	347	155	351	1.96
BR-62	1.4	138	278	139	0.77
BR-63	2.1	188	284	190	0.94
BR-64	3.3	194	229	198	0.94
BR-65	3.7	236	305	240	1.40
BR-66	2.5	190	284	193	1.26
BR-67	5.7	332	343	338	2.20
BR-68	6.1	374	313	380	2.42
BR-69	4.1	268	263	272	1.62
BR-70	16.5	592	364	609	3.27

The amount of exchangeable K (Ex-K) varied between 38.1 and 1,014 mg/kg and was composed of K in clay minerals and soil organic matter. This form of K quickly reaches equilibrium with the K in soil solution and is, therefore, readily accessible to plants. It appears that minerals and land management influenced high Ex-K in research site. Clay minerals found in the site included smectite and vermiculite that can adsorb K both in outer or inner layer of clay minerals, thereby increasing the retention of Ex-K. Land management, such as the application of inorganic synthetic fertilizers, including K fertilizers, also affected high Ex-K. K fertilization could be reduced in soils containing clay smectite so that Ex-K is reduced to a certain extent and can be replenished from non-exchangeable forms (Gawander et al. 2002). The high concentration of exchangeable Ca was caused by calcareous sandstone and napal parent materials, shown by high CEC, as they contain smectite or clay minerals 2:1. Results of this research observed that Ex-K has a significant positive correlation with exchangeable Ca (Table 5). This phenomenon indicates that Ex-K does not exhibit the nature of antagonism with exchangeable Ca.

Table 5. Correlation coefficients of K contents in various forms with soil properties (n = 61)

Soil properties	Water-K	Ex-K	NE-K
 (mg/kg)		
Clay (%)	0.104	0.130	0.391**
Sand (%)	-0.127	-0.091	-0.543**
Silt (%)	-0.004	-0.103	0.082
Organic C (%)	-0.078	0.010	-0.498**
CEC (cmol/kg)	0.128	0.116	0.341**
Exchangeable Ca (cmol/kg)	0.193	0.309*	0.236
Exchangeable Mg (cmol/kg)	0.065	-0.025	0.318*
K saturation (%)	0.671**	0.873**	-0.025

* Significant ($p < 0.05$); **Very significant ($p < 0.01$)

Non-exchangeable K (NE-K) varies from 14.4 to 621.8 mg/kg (Table 4). Furthermore, strong positive correlations between NE-K and CEC, clay content, and exchangeable Mg were observable, as shown in Table 5. Sands negatively contribute to NE-K (Table 5), while clays have a relatively high NE-K. The research indicated that clay minerals contained abundant K. Present study found that most soils exposed a high content NE-K (greater than 300 mg/kg, see Table 4), consistent with a previous literature (Rao et al. 2010). Weathering process of mica minerals, such as illite, smectite, vermiculite, and their combinations, plays a significant role in supplying K to the soil (Andrist-Rangel et al. 2006), which is also reflected in a tropical area studied in this article. Soils containing ample vermiculite and mica minerals are characterized by high amounts of NE-K (Martin and Sparks 1985). This research suggested that NE-K was balanced with Ex-K and water-soluble K, serving as a crucial K reservoir (Hartono et al. 2023). Due to this equilibrium, some K from fertilizers can be transformed into NE-K form. The soil in Brebes Regency, Central Java, Indonesia had a high capacity to adsorb K. NE-K desorption in soils is directly related to 2:1 clay mineral (Britzke et al. 2012). Vermiculite content influenced CEC in clay fraction; meanwhile, higher smectite content was associated with higher CEC. Content of NE-K was negatively correlated with organic C content, suggesting that organic C rate had an inverse relationship with CEC. This is because the status of organic C was low. Despite this, soil negative charge remained high due to the presence of 2:1 clay mineral. Exchangeable Mg was also positively correlated with NE-K, suggesting that exchangeable Mg was also related to 2:1 clay mineral. There is a greater preference for Ca in vermiculite with low Mg saturation (Levy and Shainberg 1972). Cations with low hydration energies, such as K, cause dehydration and are placed between layers of clay minerals. In contrast, cations with high hydration energies, such as Ca and Mg, produce hydrated and dilated interlayer spaces and easily migrate during exchange reactions (Douglas 1989).

Water-K and Ex-K are readily available to plants; hence, they are favorable indicators for K uptake. On the other hand, NE-K could be slowly available. This study discovered that Avail-K soil was found in all sites, including the high group (>50 mg/kg). This form of K measures availability of K; nonetheless, interpretation should be carefully taken, especially when used in a long-term data assessment or domination of 2:1 clay mineral exists. NE-K is a reserve that is potentially valuable to provide K.

This research indicated that the outcome for K fertilization can vary depending on the soil type. For instance, clay minerals with a layered structure which possesses a high surface area and high negative charge (such as illite and vermiculite), tend to retain more K than clay minerals with a lower charge (such as kaolinite). Ex-K represented only a small portion of potassium extractable with HNO₃ in

smectite soils. Therefore, determination of both Ex-K and NE-K would likely give a better description of potential supplies of K in soils.

The amount of residual K from added K that remained in the soil solution did not depend on the amount of K applied to the soil. This was due to the presence of large amounts of clay minerals, such as illite and vermiculite, in the soil. This suggests that soils containing illite and vermiculite clay minerals cause K added through fertilizer to be partially bound to the clay mineral interlayer. The fixation rate in these Inceptisol soils varied from 25.5% in soils with mixed clay mineral composition to 71.0% in soils with high amounts of illite and vermiculite clay minerals. The release of K from weathered minerals in the soil can support plant nutrition for an extended period. However, if soil K levels are depleted, the effectiveness of K fertilization may be limited owing to its fixation in a NE-K form, which reduces its availability to plants (Portela et al. 2019). In soils with high illite content and weathering, there can be significant changes in the dynamics of K and clay minerals, which can alter the amounts of K in various forms, particularly in NE-K forms (2:1 position in clay mineral layers) (Moterle et al. 2016). If fertilization is high, the concentration of K in the soil may increase, leading to increased uptake by plants and potentially excessive K consumption (Gommers et al. 2005). Kaolinitic soil has a higher water-soluble K concentration than mixed or smectitic soil, although the Ex-K content in the soil is the same (Sharpley 1989).

Q/I K parameters. Balanced K in soils, known as the equilibrium activity ratio of K (ARE^K), represents the amount of K readily available for plant absorption (Panda and Patra 2018). Its values ranged from 0.0004–0.0182 (mol/L)^{1/2} (Table 6). ARE^K values below 0.001 (mol/L)^{1/2} correspond to K adsorption in a "wedge" or interlayer position, while values above 0.01 (mol/L)^{1/2} indicate adsorption at a planar position. K adsorption occurs at the "edge" position when ARE^K is within the range of 0.001 to 0.01 (mol/L)^{1/2} (Van Schouwenburg and Schuffelen 1963). Observed ARE^K values in this study suggested that majority of adsorbed K is located in the edge plane with a value ranging between 0.001–0.01 (mol/L)^{1/2}. In soils containing 2:1 clay mineral, K is derived from the clay minerals themselves, whereas in soils having 1:1 clay mineral, only a small amount of K is present. As concentration of Ca in surrounding solution increases, the value of K declines, causing ARE^K to drop (Schneider 1997). High ARE^K values are typically associated with K fertilization (Sparks and Liebhardt 1981) or naturally high Ex-K (Jimenez and Parra 1991; Schindler et al. 2005). K fertilization led to higher ARE^K values (Beckett 1964; Le Roux and Sumner 1968). The present study indicated that significant correlation ($p < 0.01$) was observed between ARE^K and Ex-K, indicating that K in the soil solution was in equilibrium with Ex-K (Table 7).

Table 6. Quantity and intensity parameters of observed soils

Sample code	Linear Equation	R ²	ARE^K	ΔK^0	PBC ^K	ΔG
			(mol/L) ^{1/2}	(cmol/kg)	(cmol/kg)/(mol/L) ^{1/2}	(kJ/mol)
B-1	Y=221.68x - 0.7847	0.974	3.5 x 10 ⁻³	-0.78	222	-14.0
B-2	Y=269.77x - 0.6499	0.988	2.4 x 10 ⁻³	-0.65	270	-14.9
B-3	Y=219.1x - 0.79	0.993	3.6 x 10 ⁻³	-0.79	219	-13.9
B-4	Y=251.63x - 0.6759	0.961	2.7 x 10 ⁻³	-0.68	252	-14.7
B-5	Y=138.8x - 2.5235	0.944	1.82 x 10 ⁻²	-2.52	139	-9.93
B-6	Y=194.21x - 0.4966	0.927	2.6 x 10 ⁻³	-0.50	194	-14.8
B-7	Y=231.86x - 1.0934	0.968	4.7 x 10 ⁻³	-1.09	232	-13.3

Sample code	Linear Equation	R ²	ARe ^K	ΔK ⁰	PBC ^K	ΔG
			(mol/L) ^{1/2}	(cmol/kg)	(cmol/kg)/ (mol/L) ^{1/2}	(kJ/mol)
B-8	Y=190.54x - 0.2953	0.975	1.5 x 10 ⁻³	-0.30	191	-16.0
B-9	Y=222.44x - 0.6641	0.981	3.0 x 10 ⁻³	-0.66	222	-14.4
B-10	Y=196.54x - 0.1843	0.952	0.9 x 10 ⁻³	-0.18	197	-17.3
B-11	Y=118.67x - 0.6798	0.996	5.7 x 10 ⁻³	-0.68	119	-12.8
B-12	Y=110.94x - 1.7878	0.955	1.61 x 10 ⁻²	-1.79	111	-10.2
B-13	Y=231.86x - 0.332	0.966	1.4 x 10 ⁻³	-0.33	232	-16.2
B-14	Y=217.45x - 0.5247	0.937	2.4 x 10 ⁻³	-0.52	217	-14.9
B-15	Y=187.2x - 0.3582	0.933	1.9 x 10 ⁻³	-0.36	187	-15.5
B-16	Y=202.88x - 0.6255	0.789	3.1 x 10 ⁻³	-0.63	203	-14.3
B-17	Y=95,446x - 0.6616	0.959	6.9 x 10 ⁻³	-0.66	95	-12.3
B-18	Y=140.37x - 0.1574	0.801	1.1 x 10 ⁻³	-0.16	140	-16.8
B-19	Y=111.57x - 0.615	0.977	5.5 x 10 ⁻³	-0.62	112	-12.9
B-20	Y=120.19x - 0.7965	0.988	6.6 x 10 ⁻³	-0.80	120	-12.4
B-21	Y=101.66x - 0.1082	0.959	1.1 x 10 ⁻³	-0.11	102	-17.0
B-22	Y=154.63x - 0.2326	0.962	1.5 x 10 ⁻³	-0.23	155	-16.1
B-23	Y=155.17x - 0.3595	0.993	2.3 x 10 ⁻³	-0.36	155	-15.0
B-24	Y=251.63x - 0.6759	0.961	2.7 x 10 ⁻³	-0.68	252	-14.7
B-25	Y=43,165x - 0.2049	0.824	4.7 x 10 ⁻³	-0.20	43	-13.3
BR-4	Y=114.87x - 0.8026	0.924	7.0 x 10 ⁻³	-0.80	115	-12.3
BR-13	Y=220.25x - 0.0996	0.998	0.5 x 10 ⁻³	-0.10	220	-19.1
BR-14	Y=149.54x - 0.1645	0.967	1.1 x 10 ⁻³	-0.16	150	-16.9
BR-14-BM	Y=166.69x - 0.8709	0.966	5.2 x 10 ⁻³	-0.87	167	-13.0
BR-15	Y=128.37x - 0.5705	0.959	4.4 x 10 ⁻³	-0.57	128	-13.4
BR-18	Y=221.68x - 0.7847	0.974	3.5 x 10 ⁻³	-0.78	222	-14.0
BR-19	Y=269.77x - 0.6499	0.988	2.4 x 10 ⁻³	-0.65	270	-14.9
BR-21	Y=219.1x - 0.79	0.993	3.6 x 10 ⁻³	-0.79	219	-13.9
BR-26	Y=251.63x - 0.6759	0.961	2.7 x 10 ⁻³	-0.68	252	-14.7
BR-28	Y=138.8x - 2.5235	0.944	1.82 x 10 ⁻²	-2.52	139	-9.93
BR-34	Y=194.21x - 0.4966	0.927	2.6 x 10 ⁻³	-0.50	194	-14.8
BR-42	Y=231.86x - 1.0934	0.968	4.7 x 10 ⁻³	-1.09	232	-13.3
BR-43	Y=190.54x - 0.2953	0.975	1.5 x 10 ⁻³	-0.30	191	-16.0

Quantity-intensity relationship of soil potassium.....

Sample code	Linear Equation	R ²	ARe ^K	ΔK ⁰	PBC ^K	ΔG
			(mol/L) ^{1/2}	(cmol/kg)	(cmol/kg)/ (mol/L) ^{1/2}	(kJ/mol)
BR-45	Y=222.44x - 0.6641	0.981	3.0 x 10 ⁻³	-0.66	222	-14.4
BR-46	Y=196.54x - 0.1843	0.952	0.9 x 10 ⁻³	-0.18	197	-17.3
BR-47	Y=221.68x - 0.7847	0.974	3.5 x 10 ⁻³	-0.78	222	-14.0
BR-48	Y=269.77x - 0.6499	0.988	2.4 x 10 ⁻³	-0.65	270	-14.9
BR-50	Y=219.1x - 0.79	0.993	3.6 x 10 ⁻³	-0.79	219	-13.9
BR-51	Y=251.63x - 0.6759	0.961	2.7 x 10 ⁻³	-0.68	252	-14.7
BR-54	Y=138.8x - 2.5235	0.944	1.82 x 10 ⁻²	-2.52	139	-9.9
BR-55	Y=194.21x - 0.4966	0.927	2.6 x 10 ⁻³	-0.50	194	-14.8
BR-56	Y=231.86x - 1.0934	0.968	4.7 x 10 ⁻³	-1.09	232	-13.3
BR-57	Y=190.54x - 0.2953	0.975	1.5 x 10 ⁻³	-0.30	191	-16.0
BR-58	Y=222.44x - 0.6641	0.981	3.0 x 10 ⁻³	-0.66	222	-14.4
BR-59	Y=196.54x - 0.1843	0.952	0.9 x 10 ⁻³	-0.18	197	-17.3
BR-60	Y=134.4x - 0.1444	0.992	1.1 x 10 ⁻³	-0.14	134	-16.9
BR-61	Y=121.56x - 0.6333	0.980	5.2 x 10 ⁻³	-0.63	122	-13.0
BR-62	Y=258.82x - 0.106	0.987	0.4 x 10 ⁻³	-0.11	259	-19.3
BR-63	Y=278.19x - 0.3429	0.981	1.2 x 10 ⁻³	-0.34	278	-16.6
BR-64	Y=213.77x - 0.4314	0.961	2.0 x 10 ⁻³	-0.43	214	-15.4
BR-65	Y=150.31x - 0.37	0.988	2.5 x 10 ⁻³	-0.37	150	-14.9
BR-66	Y=120.05x - 0.2765	0.937	2.3 x 10 ⁻³	-0.28	120	-15.1
BR-67	Y=156.84x - 0.8736	0.961	5.6 x 10 ⁻³	-0.87	157	-12.9
BR-68	Y=173.7x - 0.7163	0.994	4.1 x 10 ⁻³	-0.72	174	-13.6
BR-69	Y=175.41x - 0.6681	0.944	3.8 x 10 ⁻³	-0.67	175	-13.8
BR-70	Y=132.93x - 1.4471	0.987	1.09 x 10 ⁻²	-1.45	133	-11.2

Table 7. Correlation between Q/I K parameters and some soil properties

Correlation (n = 61)	ARe^K	ΔK⁰	PBC^K	ΔG	Clay	Ex-K	CEC
ARe ^K	1						
ΔK ⁰	-0.942**	1					
PBC ^K	-0.414**	0.133	1				
ΔG	0.865**	-0.853**	-0.385**	1			
Clay	0.035	-0.001	-0.030	-0.029	1		
Ex-K	0.463**	-0.416**	-0.223	0.410**	0.129	1	
CEC	-0.115	0.123	0.067	-0.120	0.504**	0.116	1

* Significant ($p < 0.05$); **Very significant ($p < 0.01$)

ΔK⁰ represents the quantity of K available in the soil (Rupa et al. 2003). Increasing ΔK⁰ or negative values indicates a greater release of K into soil solution, thereby making more potassium available to plants. Compared to exchangeable K obtained through ammonium acetate extraction, ΔK⁰ provides a more accurate estimate of K available to plants (Sparks and Liebhardt 1981). Soils containing many clays minerals host K on a specific surface, so ammonium from ammonium acetate can replace K from the surface and yielding a higher exchangeable K (Richards and Bates 1988). Measured ΔK⁰ in research site varied from -0.10 to -2.52 cmol/kg, as shown in Table 6. Higher negative value of ΔK⁰ suggested a higher amount of K is released into the soil due to fertilization (Rupa et al. 2003). Additionally, strong negative correlation ($r = -0.942^{**}$) between ARe^K to ΔK⁰ indicated that ΔK⁰ played a significant role in determining availability of soil potassium (Table 7). This means that the higher the adsorbed K is in the edge/wedge plane of clay minerals, the lower the ΔK⁰. At B-10 and BR-13 sites, observed ARe^K was low (< 0.001 (mol/L)^{1/2}), indicating that K was adsorbed into clay minerals in the wedge position. This condition was also supported by the fact that clay minerals at both locations contained vermiculite and illite (Table 3). High exchangeable K compared to ΔK⁰ suggested that K was more specifically bound (Sparks and Liebhardt 1981). This is because the clay content was relatively high, and clay minerals contained 2:1 type (Table 3); hence, the amount of K on the specific surface was fairly large. This is also supported by significant negative relationship between ΔK⁰ and exchangeable K. Soil samples from the research site exhibited a higher ΔK⁰ than exchangeable K, implying that these soils released K through dissolution or diffusion, rather than by exchange (Abaslou and Abtahi 2008).

High PBC^K signifies that the level of K in the soil is adequate and has the capability to replenish K in soil solution (Beckett 1964). PBC^K values can be classified as very low (< 20 (cmol/kg)/(mol/L)^{1/2}), low (20-100 (cmol/kg)/(mol/L)^{1/2}), elevated (100-200 (cmol/kg)/(mol/L)^{1/2}), or high (> 200 (cmol/kg)/(mol/L)^{1/2}) (Zharikova 2004). High PBC^K suggests a consistent availability of K in the soil solution over an extended period (Panda and Patra 2018). This research found that PBC^K varied greatly, around 43.17 – 278.19 (cmol/kg)/(mol/L)^{1/2}. ARe^K was found to be negatively correlated with PBC^K (Table 7). The present study suggests that intensive planting can reduce the equilibrium activity ratio of K. This is consistent with the results of Rupa et al. (2001) and Roux and Summer (1968) stating that high PBC^K in soils due to intensive planting is observable as potassium is preferable, especially in soils with very low K saturation. Potassium deficiency in soils is seen when K saturation is less than 2.00% (Lu et al. 2020). Observed soils with low K saturation (0.20–1.96%), therefore, exposing a risk of K deficiency except in locations B-5, B-12, BR-4, BR-14-BM, BR-34, BR-43, BR-46, BR-54, BR-67, BR-68, and BR-70. Soils with high PBC^K are characterized by low K saturation and have a higher potential to restore K in soil solution.

Free energy of K, or ΔG , is an indicator of potential K content in the soil. Significance of ΔG extends the accessibility of K and Ca. Free energy exchange is linked to standard chemical equivalent of K by substituting one chemical equivalent of Ca in clays and releasing a specific amount of caloric energy (Rupa et al. 2003). Observed ΔG value ranged from -9.93 to -19.33 kJ/mol. Soils with ΔG values ranging from -17 to -15 kJ/mol indicate deficiency of K in plants. Values spanning between -15 and -8.4 kJ/mol are considered sufficient, while those exceeding -8.4 kJ/mol are considered to have an excessive K (McLean 1976). Based on these ranges, the average (-14.45 kJ/mol) indicated that sufficient K in plants was found in the shallot production center (Table 6). It should be noted, however, that potential lacking K remains. The present study discovered that ΔG was negatively correlated in significant level with ΔK^0 , PBC^K and Ex-K and was significantly positive with ARe^K (Table 7). A comparable relation was observed between ΔG , ARe^K , ΔK^0 , and PBC^K (Abaslou and Abtahi 2008). Generally, greater changes in potassium's free energy within the soil correspond to lower K saturation. This suggests that lower concentration of K in a solution is more easily replaceable than higher concentrations, where releasing K from the reserves requires more energy.

Soils in the shallot cultivation of Brebes Regency have a high PBC^K at low K saturation, and the soil can efficiently release K into soil solutions. Therefore, using K fertilizer can be optimized with the appropriate dosage, thus preventing excessive fertilizer application, which can increase costs and potentially cause environmental pollution. The high Ex-K content in soils with a clay texture indicates that these soils have a natural ability to provide K for plants. This management should pay attention to the release of K that is already available so that additional fertilization can be adapted to the specific needs of plants at various stages of growth. ARe^K varies depending on clay minerals, and periodic monitoring of K availability is important to ensure that plants obtain sufficient K. This can be achieved by periodically analyzing the soil to determine the available K status and adjusting the fertilization strategy. Managing K nutrients must align with agricultural sustainability efforts in which excessive K fertilization can cause environmental pollution. Fertilization strategies should consider releasing K from the natural sources of soil and plant needs to maximize yields without damaging soil ecosystems. Thus, the management of K nutrients in Brebes Regency can be improved through a data-based approach based on analyzing the quantity-intensity relationship (Q/I). This approach will support more efficient, sustainable, and productive agricultural practices for shallot farmers in the region.

Therefore, in soils containing 2:1 type clay mineral, the ARe^K , PBC^K , and ΔK^0 parameters need to be analyzed. Further research will model the parameters of ARe^K , PBC^K , and ΔK^0 through the machine learning (ML) approach by including environmental covariates that can be used as predictors in the ML algorithm. For better K fertilization recommendations, further research is needed, namely, fertilization experiments in a greenhouse or field to determine the relationship between plant K nutrient uptake with ARe^K , PBC^K , and ΔK^0 , and to validate the model. Thus, the model that will be built to determine the parameters ARe^K , PBC^K , and ΔK^0 can facilitate the determination of fertilization recommendations, especially for K fertilizer.

CONCLUSION

Soils in the shallot cultivation central of Brebes contained relatively low K saturation, while Ex-K was classified as high. High Ex-K was influenced by the type of clay minerals and land management. The NE-K content was also relatively high. This showed that clay minerals in the soil was holding a great amount of K. The K equilibrium activity ratio (ARe^K) varied with the mean K in edge-positioned 2:1 clay mineral. High Ex-K does not necessarily reflect high K activity. A negative value of labile K (ΔK^0) signified a higher release of K into the soil solution, leading to a larger quantity of K being available for absorption by plants or being easily leached out. The PBC^K values were relatively high with low K saturation indicating a risk of experiencing K deficiency. Averaged free energy (ΔG) value suggested sufficient K for plants, despite the existence of potential deficiency of K. This research emphasized the importance of Q/I evaluation to better understand the characteristics and behavior of

soil potassium, with the presence of specific clay minerals. The outcome of the research indicated the necessity of re-examination of current K fertilization scheme to improve the efficiency of K fertilization.

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REFERENCES CITED

- Abaslou, H. and A. Abtahi. 2008. Potassium quantity-intensity parameters and its correlation with selected soil properties in some soils of Iran. *Journal of Applied Sciences*. 8:1875–1882.
- Ajiboye, A.G., J.O. Azeez, and A.J. Omotunde. 2015. Potassium forms and quantity–intensity relationships in some wetland soils of Abeokuta, Southwestern Nigeria. *Archives of Agronomy and Soil Science*. 61:1393–1408. doi:10.1080/03650340.2015.1004319.
- Al-Jumaily, M.M., H.M. Al-Hamandi, M.A. Al-Obaidi, and R.R. Al-Ziand. 2022. Quantity-intensity ratio of potassium in gypsiferous soils in Iraq. *Pesquisa Agropecuária Tropical*. 52:e71620. doi:10.1590/1983-40632022v5271620.
- Andrist-Rangel, Y., M. Simonsson, S. Andersson, I. Öborn, and S. Hillier. 2006. Mineralogical budgeting of potassium in soil: A basis for understanding standard measures of reserve potassium. *Journal of Plant Nutrition and Soil Science*. 169:605–615. doi:10.1002/jpln.200621972.
- Balai Penelitian Tanah. 2021. Rekomendasi Pemupukan Tanaman Hortikultura per Kabupaten Se-Indonesia. Baand Penelitian and Pengembangan Pertanian Kementerian Pertanian, Bogor, Indonesia.
- Beckett P. 1972. Critical cation activity ratios. *Advances in Agronomy*. 24: 379-412. doi: 10.1016/S0065-2113(08)60639-2.
- Beckett PHT. 1964. Studies on soil potassium: I. Confirmation of the ratio law: Measurement of potassium potential. *Journal of Soil Science*. 15(1):1–8. doi:10.1111/j.1365-2389.1964.tb00239.x.
- Bekele, M. 2018. Effects of different levels of potassium fertilization on yield, quality and storage life of onion (*Allium cepa* L.) at Jimma, Southwestern Ethiopia. *Journal Food Science Nutrition*. 1:32-9.
- Badan Pusat Statistik Kabupaten Brebes. 2022. Badan Pusat Statistik Kabupaten Brebes (in Bahasa Indonesia). [diunduh 2022 Agu 30]. Tersedia pada: <https://brebeskab.bps.go.id/subject/151/iklim.html#subjekViewTab3>.
- Bilias, F. and N. Barbayiannis. 2018. Contribution of non-exchangeable potassium on its quantity-intensity relationships under K-depleted soils. *Archives of Agronomy and Soil Science*. 64: 1988-2004. doi:10.1080/03650340.2018.1472376.
- Britzke, D., L.S. Da Silva, D.F. Moterle, D. dos Santos Rheinheimer, and E.C. Bortoluzzi. 2012. A study of potassium dynamics and mineralogy in soils from subtropical Brazilian lowlands. *Journal of Soils and Sediments*. 12:185–197. doi:10.1007/s11368-011-0431-7.

- Datta, S.C. and T.G. Sastry. 1988. Determination of threshold levels for potassium release in three soils. *Journal of the Indian Society of Soil Science*. 36: 676– 681.
- Douglas, L.A. 1989. Vermiculites pp. 635–674. In *Minerals in Soil Environments*. John Wiley & Sons, Ltd.
- Gawander, J.S., P. Gangaiya, and R.J. Morrison. 2002. Potassium studies on some sugarcane growing soils in Fiji. *The South Pacific Journal of Natural and Applied Sciences*. 20:15–21. doi:10.1071/sp02004.
- Gomez, K.A. and A.A. Gomez. 1984. *Statistical Procedures for Agriculture Research*. 2nd Ed. John Wiley and Sons. New York.
- Gommers, A., Y. Thiry, and B. Delvaux. 2005. Rhizospheric mobilization and plant uptake of radiocesium from weathered micas. *Journal of Environmental Quality*. 34:2167. doi:[10.2134/jeq2004.0406](https://doi.org/10.2134/jeq2004.0406).
- Griffin, B.A. and J.J. Jurinak. 1973. Estimation of activity coefficients from the electrical conductivity of natural aquatic systems and soil extracts. *Soil Science*. 116:26–30.
- Hamand, J., C.P. Burnham, and B. Ruhana. 1999. Evaluation of quantity-intensity relationships of potassium in deeply weathered soil profile developed over granite from peninsular Malaysia. *Communications in Soil Science and Plant Analysis*. 30:17-18, 2311-2321. doi: 10.1080/00103629909370375.
- Hartono, A., D. Nadalia, and B.H. Trisasongko. 2023. Soil potassium adsorption at several shallot center areas, Brebes Regency, Central Java Province. *Journal of Degraded and Mining Lands Management*. 10:4737-4747. doi:10.15243/jdmlm.2023.104.4737.
- Hasan, MD.R. 2019. Effect of potassium on the yield of onion [Thesis]. Department of Soil Science Sher-E-Bangla Agricultural University (Sau) Sher-E-Bangla Nagar, Dhaka, Bangladesh.
- Havlin, J.L., S.L. Tisdale, W.L. Nelson, and J.D. Beaton. 2014. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. Pearson Inc.
- Helmke, P.A., and D.L. Sparks. 1996. Lithium, Sodium, Potassium, Rubidium, and Cesium. In D.L. Sparks, A.L. Page, P.A. Helmke, and R.H. Loeppert (eds.) *Methods of Soil Analysis. Part 3. Chemical Methods*. SSSA. Book Series No.5. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, USA. 551-574 p.
- Huang, P.M. 2005. Chemistry of potassium in soils. *Chemical Processes in Soils*. 8:227–292. doi:10.2136/sssabookser8.c4.
- Indonesian Center for Agricultural Land Resources Research and Development (ICALRD). 2017. *Soil Map of Brebes Regency 1:50,000*.
- Islam, A., A.S. Karim, A.R.M. Solaiman, M.S. Islam, and M.A. Saleque. 2017. Eight-year long potassium fertilization effects on quantity/intensity relationship of soil potassium under double rice cropping. *Soil and Tillage Research*. 169:99–117. doi:10.1016/j.still.2017.02.002.
- Jalali, M. 2007. A study of the quantity/intensity relationships of potassium in some calcareous soils of Iran. *Arid Land Research and Management*. 21:133–141. doi: 10.1080/15324980701236382.
- Jimenez, C. and M.A. Parra. 1991. Potassium quantity-intensity relationships in calcareous vertisols and inceptisols of Southwestern Spain. *Soil Science Society of America Journal*. 55:985–989. doi:10.2136/sssaj1991.03615995005500040015x.

- Khan, S.A., R.L. Mulvaney, and T.R. Ellsworth. 2014. The potassium paradox: Implications for soil fertility, crop production and human health. *Renewable Agriculture and Food Systems*. 29:3–27. doi:10.1017/S1742170513000318.
- Le Roux, J. and M.E. Sumner. 1968. Labile potassium in soils I: factors affecting the quantity-intensity (Q/I) parameters. *Soil Science*. 106:35–41.
- Levy, R. and Shainberg, I. 1972. Calcium-Magnesium Exchange in Montmorillonite and Vermiculite. *Clays and Clay Minerals*. 20:37–46. doi:10.1346/CCMN.1972.0200105.
- Liu, Y., B. Zhang, C. Li, F. Hu, and B. Velde. 2008. Long-term fertilization influences on clay mineral composition and ammonium adsorption in a rice paddy soil. *Soil Science Society of America Journal*. 72:1580–1590. doi:10.2136/sssaj2007.0040.
- Lu, J., T. Yang, X. Su, H. Qi, X. Yao, T. Cheng, Y. Zhu, W. Cao, and Y. Tian. 2020. Monitoring leaf potassium content using hyperspectral vegetation indices in rice leaves. *Precision Agriculture*. 21:324–348. doi: 10.1007/s11119-019-09670-w.
- Lumbanraja, R., J. Lumbanraja, H. Norvpriansyah, and M. Utomo. 2020. Perilaku pertukaran kalium (K) dalam tanah, K terangkut serta produksi jagung (*Zea mays* L.) akibat olah tanah and pemupukan di Tanah Ultisol Gedung Meneng pada musim tanam ketiga. *Journal of Tropical Upland Research*. 2:1–15. doi:10.23960/jtur.vol2no1.2020.69.
- Martin, H.W. and D.L. Sparks. 1985. On the behavior of nonexchangeable potassium in soils. *Communications in Soil Science and Plant Analysis*. 16:133–162.
- McLean, E.O. 1976. Exchangeable K levels for maximum crop yields on soils of different cation exchange capacities. *Communications in Soil Science and Plant Analysis*. 7:823–838. doi:10.1080/00103627609366690.
- Moody, P.W. and M.J. Bell. 2006. Availability of soil potassium and diagnostic soil tests. *Soil Research*. 44:265–275. doi:10.1071/SR05154.
- Moterle, D.F., J. Kaminski, D. dos Santos Rheinheimer, L. Caner, and E.C. Bortoluzzi. 2016. Impact of potassium fertilization and potassium uptake by plants on soil clay mineral assemblage in South Brazil. *Plant Soil*. 406:157–172. doi:10.1007/s11104-016-2862-9.
- Muliana, S. Anwar, A. Hartono, A.D. Susila, and S. Sabiham. 2018. Pengelolaan and pemupukan fosfor and kalium pada pertanian intensif bawang merah di empat Desa di Brebes. *Jurnal Hortikultura Indonesia*. 9:27–37. doi:10.29244/jhi.9.1.27-37.
- Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In D.L. Sparks, A.L. Page, P.A. Helmke, and R.H. Loeppert (eds.) *Methods of Soil Analysis. Part 3. Chemical Methods*. SSSA. Book Series No.5. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, USA. 995-996 p.
- Nursyamsi, D., K. Idris, S. Sabiham, D.A. Rachim, and A. Sofyan. 2007. Dominant soil characteristics that effect on available K at smectitic soils. *Indonesian Soil and Climate Journal*. 26: 13-28..
- Oumar, K.O., N.N. Gilbert François, M.M. Bertrand, T. Nathanael, B.E. Constantin, M.J. Simon, and E. Jacques. 2022. Mineralogical, geochemical characterization and physicochemical properties of kaolinitic clays of the Eastern Part of the Douala Sub-Basin, Cameroon, Central Africa. *Applied Sciences*. 12:9143. doi: 10.3390/app12189143.
- Panda, R. and S.K. Patra. 2018. Quantity-intensity relations of potassium in representative coastal soils of eastern India. *Geoderma*. 332:198–206. doi: 10.1016/j.geoderma.2018.07.014.

- Pansu, M. and J. Gautheyrou. 2006. Particel size analysis In Handbook of Soil Analysis. Mineralogic, Organic and Inorganic Methods. Springer-Verlag Berlin Heidelberg, Netherland. 35-41 p.
- Portela, E., F. Monteiro, M. Fonseca, and M.M. Abreu. 2019. Effect of soil mineralogy on potassium fixation in soils developed on different parent material. *Geoderma*. 343: 226–234.
- Prasetyo, B.H., D. Subardja, and D.B. Kaslan. 2005. Ultisols bahan volkan andesitik: diferensiasi potensi kesuburan and pengelolaannya. *Jurnal Tanah and Iklim*. 23:1–12.
- Pratt, P.F. 1965. Potassium. In *Methods of Soil Analysis, Part 2, Agron. Monogr. 9*, Ed. C.A. Black et al., p. 1022-1030, AS A, Madison
- Rao, C.S., A.S. Rao, K.V. Rao, B. Vankateswarlu, and A.K. Singh. 2010. Categorization of districts based on nonexchangeable potassium: Implications in efficient K fertility management in Indian Agriculture. *Indian Journal of Fertilisers*. 6: 40-56.
- Richards, J.E. and T.E. Bates. 1988. Studies on the potassium-supplying capacities of southern ontario soils. ii. nitric acid extraction of nonexchangeable K and its availability to crops. *Canadian Journal of Soil Science*. 68:199–208. doi:10.4141/cjss88-020.
- Rosolem, C.A. and F. Steiner. 2017. Effects of soil texture and rates of k input on potassium balance in tropical soil. *European Journal of Soil Science*. 68: 658-666. doi:10.1111/ejss.12460.
- Rupa, T.R., S. Srivastava, A. Swarup, D. Sahoo, and B.R. Tembhare. 2003. The availability of potassium in Aeric Haplaquept and Typic Haplustert as affected by long-term cropping, fertilization and manuring. *Nutrient Cycling in Agroecosystems*. 65:1–11. doi:10.1023/A:1021815821161.
- Saleque, M.A., M. Anisuzzaman, and A.Z.M. Moslehuddin. 2009. Quantity–Intensity relationships and potassium buffering capacity of four Ganges river floodplain soils. *Communications in Soil Science and Plant Analysis*. 40: 1333-1349. doi:10.1080/00103620902761320.
- Samadi, A., B. Dovlati, and M. Barin. 2008. Effect of continuous cropping on potassium forms and potassium adsorption characteristics in calcareous soils of Iran. *Soil Research*. 46:265–272. doi: 10.1071/SR07156.
- Schindler, F.V., H.J. Woodard, and J.J. Doolittle. 2005. Assessment of soil potassium sufficiency as related to quantity-intensity in montmorillonitic soils. *Communications in Soil Science and Plant Analysis*. 36:2255–2270. doi:10.1080/00103620500196630.
- Schneider, A. 1997. Release and fixation of potassium by a loamy soil as affected by initial water content and potassium status of soil samples. *European Journal of Soil Science*. 48:263–271. doi:10.1111/j.1365-2389.1997.tb00546.x.
- Sharma, V., S. Sharma, S. Arora, and A. Kumar. 2012. Quantity–intensity relationships of potassium in soils under some Guava Orchards on marginal lands. *Communications in Soil Science and Plant Analysis*. 43: 1550–1562. doi:10.1080/00103624.2012.675387.
- Sharpley, A.N. 1989. Relationship Between Soil Potassium Forms and Mineralogy. *Soil Science Society of America Journal*. 53:1023-1028. doi:10.2136/sssaj1989.03615995005300040006x.
- Shil, N.C., M.K. Alam, M.A. Saleque, R.M. Islam, and M. Jahiruddin. 2021. Quantity-to-intensity (Q/I) relationships can efficiently characterize intensively cultivated agricultural soils in Bangladesh for better potassium supplying capacity. *Spanish Journal of Agricultural Research*. 19: 1-18. doi:10.5424/sjar/2021192-15746.
- SNI 03-6787-2002 Metode Pengujian pH dengan Alat pH Meter.

- Sparks, D.L. and P.M. Huang. 1985. Physical chemistry of soil potassium. Potassium in Agriculture. 201-276 p.
- Sparks, D.L. and W.C. Liebhardt. 1981. Effect of long-term lime and potassium applications on quantity-intensity (Q/I) Relationships in Sandy Soil. Soil Science Society of America Journal. 45:786–790. doi:10.2136/sssaj1981.03615995004500040022x.
- Suarez, D.L. 1996. Beryllium, Magnesium, Calcium, Strontium, and Barium. In D.L. Sparks, A.L. Page, P.A. Helmke, and R.H. Loeppert (eds.) Methods of Soil Analysis. Part 3. Chemical Methods. SSSA. Book Series No.5. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, USA. 575-601 p.
- Sumarni, N., R. Rosliani, and R.S. Basuki. 2012. Responses of plant growth, bulb yield, and NPK uptake of shallots to several doses of N, P, and K fertilization on Alluvial soil type. Jurnal Hortikultura. 22: 366-375.
- Sumiati, E. and O.S. Gunawan. 2007. Application of mycorrhizal biofertilizer to increase the efficiency of NPK uptake and its effects on yield and quality of shallot bulbs. Jurnal Hortikultura. 17:34–42.
- Sumner, M.E., and W.P. Miller. 1996. Cation exchange capacity and exchange coefficients. In D.L. Sparks, A.L. Page, P.A. Helmke, and R.H. Loeppert (eds.) Methods of Soil Analysis. Part 3. Chemical Methods. SSSA. Book Series No.5. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, USA. 1201-1229 p.
- Tan, K.H. 1996. Determination of Soil Organic Matter. In Soil Sampling, Preparation, and Analysis. Madison, New York. 231-232 p.
- Van Schouwenburg, J.C.H. and A.C. Schuffelen. 1963. Potassium-exchange behaviour of an illite. Netherlands Journal of Agricultural Science. 11:13–22. doi: 10.18174/njas.v11i1.17567.
- Volf, M.R., C.A.C. Crusciol, A.C. de Azevedo, M.L. Thompson, J.L. Kovar, and C.A. Rosolem. 2021. Potassium bioavailability in a tropical kaolinitic soil. Agronomy. 11: 2016. doi:10.3390/agronomy11102016.
- Woodruff, C. 1955. The energies of replacement of calcium by potassium in soils. Soil Science Society of America Journal. 19:167–171. doi:10.2136/sssaj1955.03615995001900020014x.
- Zarrabi, M. and M. Jalali. 2008. Evaluation of extractants and quantity–intensity relationship for estimation of available potassium in some calcareous soils of Western Iran. Communications in Soil Science and Plant Analysis. 39: 2663–2677. doi:10.1080/00103620802358797.
- Zhang, Q.C., G.H. Wang, Y.K. Feng, P. Qian, and J.J. Schoenau. 2011. Effect of potassium fertilization on soil potassium pools and rice response in an intensive cropping system in China. Journal of Plant Nutrition and Soil Science. 174: 73-80. doi:10.1002/jpln.200900171.
- Zhang, Z., D. Liu, M. Wu, Y. Xia, F. Zhang, and X. Fan. 2021. Long-term straw returning improve soil K balance and potassium supplying ability under rice and wheat cultivation. Scientific Reports. 11: 22260. doi:10.1038/s41598-021-01594-8.
- Zharikova EA. 2004. Potential buffer capacity of soils with respect to potassium (by the example of the Amur River region). Eurasian Soil Science. 37:710–717.
- Zhu, D., J. Lu, R. Cong, T. Ren, W. Zhang, and X. Li. 2020. Potassium management effects on quantity/intensity relationship of soil potassium under rice-oilseed rape rotation system. Archives of Agronomy and Soil Science. 66: 1274-1287. doi:10.1080/03650340.2019.1663830.