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Calibration accuracy of requirement factor and sorption studies for fertilizer recommendation

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Abstract

The inconsistent and incoherent approaches by fertilizer recommendations to index crop response has prompted the search for alternative approaches. Some of the problems stem from the overlooking of fundamental soil properties that govern the soil solution, which is where plant roots absorb nutrients for growth. A comparison was made between two contrasting equilibration techniques to evaluate their precision in estimating crop response. Sorption isotherms for phosphorus (P) and potassium (K) were compared to requirement factors. Phosphorus sorption isotherms were determined following the batch equilibration technique. Potassium was developed following equilibration with graded K levels. The requirement factors of both P and K were determined following a 6-week incubation with four different levels of fertilization. Cowpea (*Vigna unguiculata*), mustard (*Brassica juncea*), and maize (*Zea mays*) were used as test crops. The growth parameters measured included biomass (g), height (cm), and leaf area index. At harvest, yield (g pot^{-1}) and uptake (mg pot^{-1}) were also recorded. Linear correlation studies were carried out to evaluate the association between treatments and the growth parameters of the tested crops. Results showed no significant difference ($p < 0.05$) in maize growth parameters between the equilibration methods, despite the sorption isotherms estimating higher levels of P and K. The sorption isotherms for P and K were 1.7 and 9.8 times higher than their respective requirement factors. The crop response, although relatively similar in both methods, was weakly correlated with the sorption-estimated nutrient levels, indicating an overestimation of nutrients. Therefore, the requirement factors were deemed to be a more precise equilibration technique for estimating nutrient levels.

Abbreviations: AAS, atomic absorption spectrometer; C, carbon; CERU, Controlled environment research unit; CNS, carbon nitrogen sulfur; HCl, hydrochloric acid; K, potassium; KCl, potassium chloride; KZN, KwaZulu Natal; LAI, leaf area index; LAN, lime ammonium nitrate; LECO, Laboratory Equipment Corporation; NaOH, sodium hydroxide; P, phosphorus; RPM, revolutions per minute; UKZN, University of KwaZulu Natal.

1 | INTRODUCTION

When all other growth-limiting factors are kept at optimal levels, the primary factor that influences crop growth in a closed agroecosystem is the amount of phosphorus (P) or potassium (K) applied (Abbas et al., 2018). Therefore, it can be assumed that yield will increase in proportion to the rates of P or K applied, unless sufficient residual levels exist from the previous planting season, or the native levels are already optimal. In such cases, the relative yield increase can be assumed to be zero, and the crop is deemed nonresponsive to external applications. In both scenarios, a soil test calibrated against yield can predict the likelihood of non-responsiveness when extrapolated beyond experimental sites, as demonstrated by Beckett (1964), Fox and Kamprath (1970), Jalali (2007), and Hue and Fox (2010).

Fertilizer recommendations based on current approaches have been shown to be inconsistent in indexing crop response (Jordan-Meille et al., 2012; Khan et al., 2014; Rice & Havlin, 1994; Römheld & Kirkby, 2010; Schauberger et al., 2018; Shirvani et al., 2005). Although the reasons are diverse, one of the primary arguments stems from a limited understanding of the soil solution, which represents the portion of the soil where nutrients are absorbed by the growing plant (Gloaguen et al., 2007; Smethurst, 2010; Smethurst et al., 2001). To overcome this issue, a new approach has been proposed, whereby the potential for phosphorus (P) (and K) to be adsorbed can be described as the difference between the amount of P added and the amount of P adsorbed, allowing for the estimation of the amount of P in the soil solution (labile) as an indicator of P potential (although, for the time being, we will overlook the methods used for measuring P in solution) and its distribution across various fractions. It is a known fact that if a straight line is drawn between P added and P released or P potential, the resulting curve produces a slope that represents the rate of change in P potential with external application (Johan et al., 2021; Liang et al., 2022; Wolde & Haile, 2015). This interpretation is not new, as it has been extensively cited following the study by Fox and Kamprath (1970) on P sorption isotherms, which provided a detailed explanation of the functionality of this concept. The levels of soil solution P are expected to vary relative to the application rates, and a plot of a straight line between the two should generate a slope with units that quantify the rate of change of P levels in solution concerning P added (Mihoub et al., 2016; Pal, 2011; Ratanavirakul et al., 2023; Samadi, 2003; Srinivasarao et al., 2007). The units of the slope should be in mg L^{-1}/kg ha^{-1}. The fundamental purpose of the units is to represent the rate of change of P in solution, with further additions of P for a given constant mass or volume of soil, as such the units might vary with experiment (Gichangi & Mnkeni, 2009; Hue & Fox, 2010). Related studies have been extensively conducted for K following work by Beckett (1964). The intensity parameter in K equilibrium studies is characterized by the activity ratio of K to Ca and Mg taken as single unit (Abaslou & Abtahi, 2008; Al-Hamandi et al., 2019; Al-Zubaidi et al., 2008). The external K requirement is then expressed as a function of buffering capacity and intensity the parameter.

Core Ideas

- Phosphorus and potassium potential can estimate available nutrients in the soil solution.
- Phosphorus and potassium potential can be estimated by subtracting the adsorbed amount, from what was applied.
- Requirement factors are a better correlation with crop response than sorption isotherms.
- The use of sorption isotherms in P and K potentials can result in the overestimation of nutrients.

In South Africa, requirement factors are widely used in equilibria studies, much like isotherms. A specific amount of the nutrient is added, and after an equilibration period, it is extracted using a particular extractant such as Mehlich, Ammonium Acetate, Olsen, or Bray I or II. The relationship between the amount of nutrient added and the amount of nutrient extracted can be plotted as a straight line, and the slope of this line is known as the requirement factor (Johnston et al., 1991, 1999). The interpretation of the slope between the amount of the added nutrient relative to its levels in soil solution is that, for every given amount of the nutrient applied per hectare, the soil test value will increase by 1 unit. Therefore, an incorrect assumption about the rate of change in P or K levels in solution with external application can lead to over or under application of fertilizers, resulting in reduced yields (Poswa et al., 2014; Elephant & Miles, 2016).

The relative change presumes an equilibrium between soil solution and solid active surfaces. If a given amount of soil is equilibrated with a known amount of P or K in the absence of sink factors (uptake, leaching immobilization), the remaining nutrients in soil solution after equilibration will serve as an index of labile and or potential P or K (these terms in the current study will be used interchangeable) (El Attar et al., 2022; Gichangi & Mnkeni, 2009; Meyer et al., 2023; Rani et al., 2023). The value of potential or labile P should be symmetrical with crop response when P is limiting. The relationship between crop response and P or K potential should be symmetrical, and this symmetry can be demonstrated using equilibration studies such as sorption isotherms or requirement factors (Elephant & Miles, 2016; Gichangi & Mnkeni, 2009; Poswa et al., 2014). The critical levels determined by these studies can be extrapolated beyond experimental sites to ensure accurate fertilizer recommendations for optimal crop growth.

The use of phosphorus and potassium sorption isotherms has been widespread in predicting nutrient availability and guiding fertilizer recommendations. However, there are existing gaps in their accuracy and reliability. The accuracy may be influenced by limitations in the experimental setup specifically the duration of equilibration. Typically, sorption isotherms are developed through 24-h incubation studies, overlooking the mid-to-long-term dynamics of soil nutrient availability (Habibiandehkordi et al., 2014; Hussain et al., 2010; Kristoffersen et al., 2020). To assess the accuracy and reliability of sorption isotherms in fertilizer recommendations, it is beneficial to compare them with equilibration studies that employ longer incubation periods, such as the requirement factors that utilize a 6-week timeframe. It was therefore hypothesized that longer incubation periods in equilibration studies, such as the requirement factors utilizing 6 weeks, would provide more accurate and reliable results compared to sorption isotherms developed through 24-h incubation studies. The main objective of this study was to compare the predictive abilities of two equilibration methods—sorption isotherms and requirement factors—in relation to crop response. Another objective of this study was to estimate the buffering capacities of P and K potentials in response to external applications.

2 | MATERIALS AND METHODS

2.1 | Study site

The glasshouse studies were conducted in the Controlled Environment Research Unit (CERU) at the University of KwaZulu-Natal (UKZN), Pietermaritzburg Campus (29°36″ S, 30°23″ E) under conditions with maximum and minimum temperatures of 26 and 16˚C, respectively. The topsoil (0–15 cm) was sampled from Umbumbulu (29˚59′15″ S—30˚42′12″ E). According to the South African classification system, the soil was classified as Tukulu while it was an Acrisol on the World reference base (Fey, 2010). The soils were air-dried and sieved to pass through <2 mm sieve.

2.2 | Soil characterization

The soils were analyzed at the KZN Department of Agriculture's soil fertility and analytical services. Soil pH was measured in both 1 M KCl and water solutions at a ratio of 1:2.5. The density of the milled samples for each soil was measured and reported as sample density (Manson & Roberts, 2000; Manson et al., 2017). Organic carbon and clay percentages were estimated using near-infrared spectroscopy. Total nitrogen was analyzed by the automated Dumas dry combustion method using the LECO CNS 2000 (LECO Corporation; Matejovic, 1996). Samples were weighed into ceramic crucibles to which 0.5 g of vanadium pentoxide was added as a combustion catalyst. The crucible was introduced into a horizontal furnace, where the sample is burned in a stream of oxygen at 1350˚C. Nitrogen is determined (as N_2) in a thermal conductivity cell. Soil samples were analyzed on a volume rather than a mass basis. Extractable phosphorus and potassium were analyzed using the Ambic 2 solution consisting of 0.25 M NH_4CO_3 + 0.01 M Na_2EDTA + 0.01 M NH_4F + 0.05 g L^{-1} Superfloc (N100), adjusted to pH 8 with a concentrated ammonia solution. Extractable calcium, magnesium, and acidity were determined in a 1 M KCl solution. A total of 25 mL of the solution was mixed with 2.5 mL of soil, and the resulting suspension was stirred at 400 rotations per minute (rpm) for 10 min using a multiple stirrer. The extracts are filtered using Whatman No. 1 paper. From the filtrate, 5 mL was diluted with 20 mL of 0.0356 M $SrCl_2$, and Ca and Mg were determined by atomic absorption. Acidity was determined by diluting 10 mL of the filtrate with 10 mL of de-ionized water containing two-to-four drops of phenolphthalein and titrated with 0.005 M NaOH.

2.3 | Equilibration methods

The buffering capacity based on sorption isotherms was developed by the batch equilibration technique as described by Fox and Kamprath (1970) for P and for K by Beckett (1964). The P and K buffering capacities based on requirement factors were determined following 6-week incubation with four different levels of P and K fertilizers. After the incubation period, extraction with Bray 1 solution (0.025 M HCl in 0.03 M NH_4F) was done. Bray 1 solution was chosen over other extracting solutions due to its higher r^2 for the soils from Umbumbulu Tu. A detailed description of the method is given by Johnston et al. (1991) and Johnston et al. (1999).

2.4 | Pot trial

Pot trials were conducted at the CERU in Pietermaritzburg UKZN (see Table 1). Treatments (T) were based on application rates (0 kg ha^{-1}—T1, 10 kg ha^{-1}–T2, 15 kg ha^{-1}—T3, and 20 kg ha^{-1}—T4) and the equilibration method (sorption isotherms and requirement factors for both P/K). Where K fertilization was compared, P and N were applied at optimum and constant rates for each plant in South Africa, and, when P was compared, K and N were applied at optimum rates. The fertilizer application rates were converted from kg ha^{-1} to mg kg^{-1}; the bulk density of the soil was used to calculate the mass of soil in 1 ha assuming topsoil depth,

TABLE 1 Quantities of phosphorus and potassium fertilizer estimated by the two methods used in this study across four treatment levels.

		Sorption isotherms (kg ha^{-1})		Requirement factors (kg ha^{-1})	
Treatments	**Application rates (kg ha^{-1})**	**P**[a]	**K**[a]	**P**[a]	**K**[a]
T1[b]	0	10	25	6.02	2.6
T2	10	100	250	60	26
T3	15	150	375	90	38
T4	20	200	500	120	51

[a]Applied nutrients were converted from kg ha^{-1} to mg kg^{-1}; bulk density of the soil was used to calculate mass of soil in 1 ha assuming topsoil depth, and the values obtained therefrom converted to 10 kg of soil in a pot. Nitrogen was applied as LAN, phosphorus as single super phosphate, and potassium as potassium chloride.
[b]No rates were added for T1 except the estimated equilibrium by the two methods.

and the values obtained therefrom were converted to 10 kg of soil in a pot. Nitrogen was applied as lime ammonium nitrate, phosphorus as single super phosphate, and potassium as potassium chloride. Border King white maize (*Zea mays*) seeds, iron gray–mixed cowpeas (*Vigna unguiculata*), and mustard (*Brassica juncea*) seeds were planted as test crops for both P and K. Three seeds of each plant were initially sown in 10 kg of soil. Two weeks after emergence, the plants were thinned to one plant per pot. The trial was replicated six times. Plants were watered as per field capacity and were grown to maturity. Weeding was done by hand as and when it was required. Plant parameters were measured during the growing period. Plant height was measured using a tape measure; chlorophyll content was measured using a spud meter, and the leaf area index (LAI) was measured using the AccuPar LP-80. Biomass was determined at harvest following drying in an oven at 70°C until constant weight (around 48 h). Grain yield was also determined for both maize and cowpea. Sampled plant material was then digested in a CEM microwave digester MARS 6 (CEM Corporation) using nitric acid. After digestion was complete, samples were prepared for analysis for P using an ultraviolet spectrometer and K using an atomic absorption spectrometer. Nutrient uptake was then determined as the amount of nutrients multiplied by biomass.

2.5 | Correlating soil test and crop response

The amount of P and K calculated at equilibrium for each soil test was correlated with oven-dry biomass, uptake, and yield of each crop under study. To calculate the amount of P or K at equilibrium using buffering capacity the following equation was used:

$$S_t = \mathrm{BC} \times \mathrm{Arates} \pm \mathcal{E} \tag{1}$$

where S_t refers to the soil test (mg L^{-1}); BC is the buffering capacity as determined by either the sorption isotherms or requirement factors, and $\mathcal{E}$ refers to an error that is associated with initial P and K levels. Arates refers to the rates applied.

Initial levels of the nutrients were not adjusted for because the same soil was used and an error term in the equilibration equations can be assumed and correlated with the initial nutrient levels.

2.6 | Statistical analysis

Statistical analysis was performed using GenStat 18th Edition. The fixed factors in the analysis included sorption isotherms, requirement factors, and treatment levels. Replicates were utilized as blocking structures and served as the random factors. An analysis of variance was conducted across all treatments. To determine significant differences, mean separation was performed using the least significant difference at a significance level of $p \leq 0.05$. Additionally, linear regression models using Microsoft Excel (2015) were employed to establish correlations between the various soil test methods and crop response parameters.

3 | RESULTS

3.1 | Soil properties

The physicochemical properties of the soil are given in Table 2. The soil used for this study is acidic in both water and KCl. Organic C% is low/moderate at 3%. The soil has low extractable P concentration (5 mg L^{-1}), which is expected to give the most crop response to P fertilization compared to high P-containing soils.

3.2 | Effect of equilibration method on crop response

The effect of the equilibration method on maize growth parameters is given in Table 3. There was no significant difference in biomass between the methods in most P treatments except for treatment 2. In K treatments, significant differences were observed for treatments 2 and 3, whereas no

TABLE 2 Selected physicochemical properties of the soil used in the study.

Soil parameters	
pH (water)	5.07
pH (KCl)	4.05
Sample density (g cm^{-3})	1.15
Organic carbon (%)	3.03
N (%)	0.19
Clay (%)	31.67
P (mg L^{-1})	5.00
K (mg L^{-1})	106.33
Ca (mg L^{-1})	352
Mg (mg L^{-1})	158
Total cations (cmol L^{-1})	4.05
Exchangeable acidity (cmol L^{-1})	0.90

significant difference was observed in treatment 4 with the p-value of 0.318 respectfully. A similar trend can be observed for height; both the P and K had no significant difference amongst the treatments except for treatment 2. Similarly, with LAI, no significant differences are observed among P treatments, whereas only treatments 2 and 3 had differences that were significant for K with p-values of 0.009 and 0.003.

The effect of the equilibration method on cowpea growth parameters is given in Table 4. Biomass in the K treatments had significant differences in all the treatments between the two methods of equilibration, with treatment 2 showing the greatest significance with a p-value of <0.001. Phosphorus had significant differences in biomass similar to K for all treatments, except for treatment 1 where the lowest amount was applied. Height showed a similar trend to potassium, with all treatments being significantly different. However, in the P treatments, height had significant differences only in treatment 2.

The growth parameters of mustard under different equilibration methods are presented in Table 5. The trend in biomass was similar to that of maize and cowpea, with only treatments 2 and 3 showing significant differences for both P and K, with p-values of 0.002 and 0.001 for K and 0.006 and 0.010 for P. Height was highly significant in all K treatments, except for treatment 4, whereas for P, only treatments 2 and 4 were significant. The LAI in the P treatments showed significant differences in treatments 2 and 4 with p-values of 0.045 and 0.063, respectively. On the other hand, K treatments showed significant differences in all the treatments with p-values <0.05.

The effect of the equilibration method on maize yield and uptake is given in Table 6. Significant differences were observed for P in treatment 2 with a p-value of 0.026, whereas no differences were observed for the other treatments. Potassium treatments had significant differences in most treatments except for treatment 4. The uptake in both P and K treatments was significant in all treatments except for P treatment 2.

The effect of the equilibration method on cowpea yield and uptake is given in Table 7. The only significant difference in yield among the P treatments was observed in treatment 2, where the P sourced from sorption isotherms resulted in a higher yield compared to the P sourced from requirement factors. For the K treatments, there was a different trend compared to the P treatments. The K from sorption had a higher yield compared to K from requirement factors in all treatments, except for treatment 4 where there were no significant differences between the two methods. The uptake had a similar trend, but no differences were observed except for treatment 1.

The effect of the equilibration method on P and K uptake by mustard is given in Table 8. Similarly, to maize and cowpea, uptake in both P and K was highest from sorption studies compared to the requirement factors except for P in treatments 1, 3, and 4.

3.3 | Correlation studies between the soil test methods and selected plant growth parameters

The relationships between the equilibration techniques and plant growth parameters are given in Table 9. The correlation between P from requirement factors and maize growth parameters was high, with r^2 values >0.93, except for uptake which had an r^2 value similar to that of sorption (0.92). The same pattern was observed for cowpea, where the correlation was stronger for P from requirement factors than for sorption studies, as shown by the higher r^2 values of over 0.97 for biomass, yield, and uptake.

The correlation between K and growth parameters was weaker in sorption studies compared to requirement factors, as evidenced by the lower r^2 values (Table 10). The highest r^2 value for K was 0.43 for biomass and 0.61 for yield.

4 | DISCUSSION

The soils used in the study are typical of those found in the KZN province, characterized by low pH resulting from moderate to high rainfall ranging from 650 to 1400 mm. The low-to-moderate P and K concentrations can be attributed to land use, where rural subsistence farmers in the area apply very little to no P and K fertilizers, with nitrogen being the only nutrient consistently applied. This lack of P and K fertilization, combined with low concentrations from the parent material, leads to reduced nutrient levels. Over time, this can be further exacerbated by nutrient mining, where nutrients are constantly removed without any replacement. Poor soil

TABLE 3 Impact of P and K fertilizations as estimated by two different equilibration techniques on maize growth parameters (biomass, height, and leaf area index).

Treatments	Maize Psorp.[a]	Preq.[b]	$LSD_{(0.05)}$	*p*-Value	Ksorp.[a]	Kreq.[b]	$LSD_{(0.05)}$	*p*-Value
	Biomass (g pot^{-1})							
1	444.3	427.7	32.33	0.157	445	422	23.7	0.053
2	502.7	463.3	24.13	0.020	508	448	17.4	0.005
3	501	497	17.21	0.423	506	455	17.9	0.007
4	498	501.7	51.29	0.787	483	468	51.1	0.318
	Height (cm)							
1	201	201	13.6	0.926	205	198	12.9	0.145
2	223	211	1.4	<0.001	231	216	24.4	0.110
3	226	219	8.6	0.073	230	225	11.7	0.173
4	224	222	12.2	0.686	231	223	18.9	0.224
	Leaf area index[c]							
1	1.69	1.67	0.311	0.808	2.03	1.89	0.225	0.115
2	2.14	2.06	0.131	0.120	2.49	2.06	0.179	0.009
3	2.19	2.12	0.094	0.093	2.48	2.11	0.087	0.003
4	2.19	2.21	0.22	0.609	2.32	2.20	0.13	0.59

Abbreviation: LSD, least significant difference.

[a]Psorp. & Ksorp.—Phosphorus and potassium fertilizers applied were estimated using sorption isotherms.

[b]Preq. & Kreq.—Phosphorus and potassium fertilizers applied were estimated using requirement factors.

[c]Leaf area index is a dimensionless quantity and does not have specific units.

TABLE 4 Impact of P and K fertilizations as estimated by two different equilibration techniques on cowpea growth parameters (biomass, height, and leaf area index).

Treatments	Cowpea Psorp.[a]	Preq.[b]	$LSD_{(0.05)}$	*p*-Value	Ksorp.[a]	Kreq.[b]	$LSD_{(0.05)}$	*p*-Value
	Biomass (g pot^{-1})							
1	12.7	10.9	2.09	0.061	13.9	10.2	1.48	0.009
2	30.3	17.4	6.41	0.013	37.9	13.2	2.82	<0.001
3	31.8	21.9	1.03	<0.001	31.3	15.9	2.72	0.002
4	33.4	26.2	3.38	0.012	30.0	17.3	3.59	0.004
	Height (cm)							
1	26.1	22.8	6.09	0.144	26.8	19.9	0.79	<0.001
2	39.4	31.9	4.13	0.016	41.7	25.8	3.85	0.003
3	39.1	37.9	7.56	0.109	38.2	29.5	0.83	<0.001
4	40.6	40.1	4.43	0.075	36.3	33.4	0.99	0.006
	Leaf area index[c]							
1	0.93	0.85	0.028	0.006	0.96	0.71	0.290	0.069
2	1.61	1.34	0.239	0.040	1.76	0.95	0.301	0.007
3	1.74	1.53	0.143	0.024	1.51	1.06	0.089	0.002
4	1.72	1.60	0.11	0.041	1.39	1.17	0.251	0.066

Abbreviation: LSD, least significant difference.

[a]Psorp. & Ksorp.—Phosphorus and potassium fertilizers applied were estimated using sorption isotherms.

[b]Preq. & Kreq.—Phosphorus and potassium fertilizers applied were estimated using requirement factors.

[c]Leaf area index is a dimensionless quantity and does not have specific units.

TABLE 5 Impact of P and K fertilizations as estimated by two different equilibration techniques on mustard growth parameters (biomass, height, and leaf area index).

Treatments	Mustard							
	Psorp.[a]	Preq.[b]	$LSD_{(0.05)}$	*p*-Value	Ksorp.[a]	Kreq.[b]	$LSD_{(0.05)}$	*p*-Value
	Biomass (g pot^{-1})							
1	26.1	24.3	2.420	0.051	25.7	23.3	2.87	0.073
2	56.7	38.1	4.525	0.006	56.8	27.3	5.17	0.002
3	55.2	48.2	3.099	0.010	49.0	29.3	2.87	0.001
4	56.5	54.6	2.239	0.063	46.7	45.0	4.17	0.120
	Height (cm)							
1	12.5	11.9	0.66	0.059	29	10	1.43	<0.001
2	27.9	21.7	4.93	0.032	39	30	2.87	0.006
3	32.6	26.0	7.56	0.065	37.3	31.3	2.48	0.009
4	38.4	30.0	2.32	0.004	35.7	34.3	6.25	0.456
	Leaf area index[c]							
1	1.5	1.4	0.16	0.192	1.6	1.4	0.13	0.020
2	1.7	1.6	0.10	0.045	1.9	1.6	0.19	0.018
3	1.7	1.7	0.13	0.580	1.6	1.7	0.21	0.041
4	1.9	1.7	0.23	0.063	1.8	1.6	0.09	0.013

Abbreviation: LSD, least significant difference.

[a]Psorp. & Ksorp.—Phosphorus and potassium fertilizers applied were estimated using sorption isotherms.

[b]Preq. & Kreq.—Phosphorus and potassium fertilizers applied were estimated using requirement factors.

[c]Leaf area index is a dimensionless quantity and does not have specific units.

TABLE 6 Impact of P and K fertilizations as estimated by two different equilibration techniques on maize yield and nutrient uptake.

Treatments	Maize							
	Psorp.[a]	Preq.[b]	$LSD_{(0.05)}$	*p*-Value	Ksorp.[a]	Kreq.[b]	$LSD_{(0.05)}$	*p*-Value
	Yield (g pot^{-1})							
1	150	143	23.6	0.348	151	136	11.38	0.030
2	183	161	15.5	0.026	190	153	12.25	0.006
3	187	185	16.5	0.939	193	164	24.5	0.038
4	181	187	11.7	0.914	184	171	14.1	0.053
	Uptake (mg pot^{-1})							
1	5.9	5.3	0.4	0.027	20.1	15.7	1.0	0.003
2	10.5	8.3	2.9	0.079	40.9	19.8	5.4	0.004
3	13.2	9.2	2.9	0.028	49.3	20.7	2.9	<0.001
4	13.2	11.1	0.7	0.006	62.7	24.4	6.7	0.002

Abbreviation: LSD, least significant difference.

[a]Psorp. & Ksorp.—Phosphorus and potassium fertilizers applied were estimated using sorption isotherms.

[b]Preq. & Kreq.—Phosphorus and potassium fertilizers applied were estimated using requirement factors.

qualities, such as low pH, can also be expected to strongly influence nutrient uptake and plant growth factors.

The absence of significant differences ($p > 0.05$) in maize growth parameters (biomass, height, and LAI) between equilibration methods suggests an overestimation of sorption buffering capacity. This overestimation is more pronounced for P than for the requirement factor buffering capacity, with a factor of 1.7, and for K, with a factor of 9.8 compared to the requirement factor. The lack of significant differences in yield, as presented in Table 6, further supports this observation, particularly for P and between the equilibration methods. The accuracy of estimating the nutrient supply ability of soils to plants using sorption isotherms has been questioned in several studies (Datta, 2011; Mahdizadeh et al., 2020; Okajima et al., 1983; Schoumans, 2013). This is because there is often a distinct hysteresis in the sorption and desorption processes. Sorption isotherm studies typically have a short equilibration period of around 16 h, which may not

TABLE 7 Impact of P and K fertilizations as estimated by two different equilibration techniques on cowpea yield and uptake.

Treatments	Cowpea Psorp.[a]	Preq.[b]	$LSD_{(0.05)}$	*p*-Value	Ksorp.[a]	Kreq.[b]	$LSD_{(0.05)}$	*p*-Value
	Yield (g pot^{-1})							
1	7.6	6.7	2.04	0.192	7.8	5.8	1.854	0.041
2	13.8	9.8	1.32	0.006	15.4	7.6	0.460	<0.001
3	13.4	12.4	1.49	0.103	13.1	8.3	1.812	0.008
4	12.9	13.7	1.75	0.541	12.6	11.5	1.995	0.069
	Uptake (mg pot^{-1})							
1	16.3	14.9	1.62	0.073	16.2	12.3	5.146	0.081
2	22.8	19.8	3.99	0.082	27.3	16.1	2.611	0.003
3	23.1	21.3	1.53	0.039	29.1	17.0	1.326	0.002
4	23.9	22.8	3.34	0.267	31.0	19.8	0.875	0.004

Abbreviation: LSD, least significant difference.
[a]Psorp. & Ksorp.—Phosphorus and potassium fertilizers applied were estimated using sorption isotherms.
[b]Preq. & Kreq.—Phosphorus and potassium fertilizers applied were estimated using requirement factors.

TABLE 8 Impact of P and K fertilizations as estimated by two different equilibration techniques on mustard nutrient uptake.

Treatments	Mustard Psorp.[a]	Preq.[b]	$LSD_{(0.05)}$	*p*-Value	Ksorp.[a]	Kreq.[b]	$LSD_{(0.05)}$	*p*-Value
	Uptake (mg pot^{-1})							
1	90.3	87.7	9.40	0.347	102.0	83.7	16.9	0.043
2	126.0	113.3	3.79	0.005	157	103	2.48	<0.001
3	140.3	122.7	24.38	0.089	149	110.3	5.74	0.001
4	147.3	131.0	24.88	0.106	145.7	117.3	17.87	0.021

Abbreviation: LSD, least significant difference.
[a]Psorp. & Ksorp.—Phosphorus and potassium fertilizers applied were estimated using sorption isotherms.
[b]Preq. & Kreq.—Phosphorus and potassium fertilizers applied were estimated using requirement factors.

be enough time for true equilibrium to be reached due to the slow reaction between applied nutrients and soil. As a result, the effectiveness of applied nutrients in accurately estimating plant growth potential may decrease. Hysteresis can be expected if soils do not reach equilibrium after the addition of nutrients, leading to a change in the nutrient sorption isotherm. Therefore, the requirement factor equilibration technique, which has an equilibration time of 6 weeks compared to 16 h for sorption isotherms, may provide a more accurate estimate. It should be noted, however, that the time required for soils to reach equilibrium with applied nutrients varies depending on the soil type and the nutrient being considered. The r^2 values presented in Table 9 provide additional evidence supporting the more accurate estimation of nutrient requirements using requirement factors compared to sorption isotherms. The higher r^2 values for biomass and yield (greater than 0.93 for both P and K) indicate a positive relationship between increasing nutrient concentration in treatments and improved crop growth. In contrast, the lower r^2 values obtained from sorption isotherms suggest a weaker correlation between soil nutrient availability and crop response.

In contrast to the yield and other growth parameters measured, the uptake of maize per pot showed significant differences in both P and K in most treatments, as indicated by *p*-values <0.05. However, these differences did not result in higher yields, suggesting very low nutrient use efficiency, which has become an essential consideration in assessing cropping systems due to the growing demand for food and limitations in fertilizer resources, as well as the environmental impact of excessive fertilizer use (Panhwar et al., 2019). This low efficiency was also observed in cowpea yield and mustard biomass (T1 and T4), where no significant differences occurred between the equilibration techniques despite higher buffering capacity values for sorption isotherms compared to the requirement factor, particularly for P.

Although the yield estimated from sorption isotherm for K was significantly higher than the requirement factor K (as shown in Table 7), it had a low correlation with

TABLE 9 Relationship between P fertilization estimated by the two equilibration techniques and selected plant parameters.

Plants parameters	Linear equations and correlations			
	$P_{sorption}$		$P_{requirement\ factor}$	
	Linear equations	Correlation coefficient	Linear equations	Correlation coefficient
Maize				
Biomass (g)	$y = 0.28x + 453.3$	$r^2 = 0.68$	$y = 0.68x + 424.6$	$r^2 = 0.95$
Yield (g pot^{-1})	$y = 0.17x + 155.2$	$r^2 = 0.68$	$y = 0.41x + 140.1$	$r^2 = 0.93$
Uptake (mg pot^{-1})	$y = 0.04x + 5.9$	$r^2 = 0.92$	$y = 0.04x + 5.0$	$r^2 = 0.98$
Cowpea				
Biomass (g)	$y = 0.10x + 14.4$	$r^2 = 0.85$	$y = 0.13x + 9.8$	$r^2 = 0.99$
Yield (g pot^{-1})	$y = 0.02x + 8.6$	$r^2 = 0.62$	$y = 0.06x + 6.2$	$r^2 = 0.98$
Uptake (mg pot^{-1})	$y = 0.03x + 16.9$	$r^2 = 0.84$	$y = 0.06x + 14.9$	$r^2 = 0.97$
Mustard				
Biomass (g)	$y = 0.15x + 30.2$	$r^2 = 0.74$	$y = 0.27x + 22.5$	$r^2 = 0.99$
Uptake (mg pot^{-1})	$y = 0.30x + 90.6$	$r^2 = 0.96$	$y = 0.38x + 87.2$	$r^2 = 0.98$

TABLE 10 Relationship between K fertilization estimated by the two equilibration techniques and selected plant parameters.

Plant parameters	Potassium			
	$K_{sorption}$		$K_{requirement\ factor}$	
	Linear equations	Correlation coefficient	Linear equations	Correlation coefficient
Maize				
Biomass (g)	$y = 0.08x + 459.7$	$r^2 = 0.38$	$y = 0.93x + 420.9$	$r^2 = 0.98$
Yield (g pot^{-1})	$y = 0.07x + 157.9$	$r^2 = 0.61$	$y = 0.73x + 134.4$	$r^2 = 0.99$
Uptake (mg pot^{-1})	$y = 0.08x + 17.9$	$r^2 = 0.99$	$y = 0.16x + 15.1$	$r^2 = 0.96$
Cowpea				
Biomass (g)	$y = 0.03x + 18.8$	$r^2 = 0.42$	$y = 0.15x + 10.1$	$r^2 = 0.90$
Yield (g pot^{-1})	$y = 0.01x + 9.4$	$r^2 = 0.38$	$y = 0.11x + 5.1$	$r^2 = 0.96$
Uptake (mg pot^{-1})	$y = 0.03x + 16.8$	$r^2 = 0.91$	$y = 0.15x + 12.1$	$r^2 = 0.99$
Mustard				
Biomass (g)	$y = 0.04x + 32.0$	$r^2 = 0.43$	$y = 0.39x + 19.5$	$r^2 = 0.74$
Uptake (mg pot^{-1})	$y = 0.09x + 111.9$	$r^2 = 0.56$	$y = 0.69x + 83.1$	$r^2 = 0.98$

treatments (as shown in Table 10), with r^2 values of only 0.38. In contrast, the requirement factor had a much higher correlation of 0.96 with K treatment. This suggests that higher K application could still result in crop response. This highlights the importance of site-specific fertilizer strategies, as emphasized by researchers such as Meyer-Aurich et al. (2010). Factors, such as spatial variations, crop physiology, and specific nutrient chemistry, are known to vary, making it difficult to understand and explain their influence on crop growth.

5 | CONCLUSION

The results of the study indicate that the use of requirement factors to estimate P and K potentials in soils is more accurate than sorption isotherms. The sorption isotherm method tends to overestimate the nutrient potential of soils, as evidenced by the lack of significant differences in growth parameters and yields between treatments estimated by sorption isotherms. In contrast, requirement factor estimated treatments had higher crop responses and better correlations with crop yields. Therefore, the requirement factor method is recommended for an accurate estimation of P and K potentials in soils, particularly in low-to-moderate P and K concentration soils like those found in the KZN province.

AUTHOR CONTRIBUTIONS

Awonke Mbangi: Data curation; formal analysis; investigation; methodology; writing—original draft. **Nqaba Nongqwenga**: Conceptualization; funding acquisition; project administration; supervision; writing—review and

editing. **Tafadzwanashe Mabhaudi**: Conceptualization; resources; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors of this study declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data used in this study will be made available up request.

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