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Dynamics of potassium and phosphorus uptake in soybean cultivated on oxisol amended with biotite schist and potassium chloride

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Abstract

Phosphorus (P) is an essential macronutrient for plant growth, but its availability to plants is often limited in acidic tropical soils by iron (Fe) and aluminum (Al) (hydr) oxides, which strongly adsorb and immobilize phosphate. This study evaluated soybean (*Glycine max* L. BRS 7582) growth in soil amended with biotite schist and a soluble potassium (K) source, potassium chloride (KCl). The experiment involved pots with dystrophic Rhodic Haplustox soil; treatments were composed by control, as KCl (KCl-T), 1% biotite schist (BSO) and biotite schist + 150 mg K kg^{-1} as KCl (BS + KCl), with all treatments receiving 100 mg P kg^{-1} as calcium dihydrogen phosphate [$Ca(H_2PO_4)_2$]. Results showed that KCl-T promoted greater shoot growth than the other treatments, presenting 9.0%, 11.9%, and 41.1% higher dry mass production compared to the BS + KCl, BSO, and control treatments, respectively. Across all sampling times, K concentration in soybean shoots was significantly higher in treatments receiving soluble K (KCl-T and BS + KCl) than in the control ($p < 0.001$). Values ranged from 11.3 to 19.4 g K kg^{-1} in KCl-based treatments, whereas the control remained below 6.7 g K kg^{-1} at all evaluation times, with BSO showing intermediate values. Notably, on the 47 day after planting, plant P uptake was statistically similar among BSO, BS + KCl, and KCl-T treatments (2.15 g P kg^{-1}; $p < 0.0001$). Soil P extractability, measured by Mehlich-1, after 37 and 47 days, increased 15.29 and 22.62% (both $p < 0.0001$) in the presence of biotite (BSO and BS + KCl), as compared to treatments without biotite (KCl-T and control); this pattern is consistent with an increase in oxalate-extractable, poorly crystalline (short-range ordered) Fe released during bioweathering, which may have contributed to P adsorption and Mehlich-extraction compared to crystalline iron/aluminum oxyhydroxides.

Keywords Crystalline iron, Nutrient availability, P adsorption, Short-range ordered Fe phases

1 Introduction

Phosphorus (P) is a highly reactive element and does not exist in its elemental form in nature. Although it is quite abundant in soils, it is mainly present as inorganic P (Pi) in insoluble complexes with cations, particularly aluminum and iron (hydr)oxides [1, 2]. Most tropical Oxisols (soils formed under intense chemical weathering in a warm, wet environment where minerals are stripped of their nutrients, leaving behind a deep, acidic, and iron-rich mineral matrix [3]) are composed mainly of crystalline oxidized minerals with high concentrations of Fe^{3+} (e.g. hematite and goethite) and aluminum (hydr)oxides (e.g. gibbsite, boehmite, diaspore). These minerals provide readily adsorbent surfaces for P [4], significantly decreasing its availability to plants.

Levels of chemically extractable P in Oxisols from the Cerrado generally range from 0.1 to 16.5 mg dm^{-3}, with 92.1% of soils having less than 2 mg dm^{-3} [5]. These values are not related to soluble P, as less than 0.1% of P is found in soil solution. Phosphorus availability depends on various factors, including soil chemical conditions and the plant species growing in it. Iron and Al oxides present variable charge depending on pH, influencing mineral surface charge and phosphate forms [3]. Iron immobilizes P mainly in acidic conditions ($pH < 5.5$), with peak adsorption at pH around 2.0 [6]. Iron and Al fix P in acidic soils; Ca takes over in alkaline soils ($pH > 7.0$). For Oxisols, an ideal pH of 6.0–6.5 minimizes Fe/Al fixation and prevents excess Ca precipitation [7]. The very low availability of P is one of the most critical conditions for adequate crop production in these soils.

Due to the high P-fixation capacity and very low available P in these soils, P must be applied in large quantities for adequate crop production [5], leading to a high accumulation of legacy P in agricultural soils [8]. It is estimated that 105 Tg of legacy P will accumulate in Brazilian agricultural lands by 2050 if the current rate of inorganic P fertilizer use continues [9].

Similarly, although mineral soils are rich in Fe, most of it exists as ferric iron (Fe^{3+}), which remains only slightly soluble within the physiological pH range under aerobic conditions. An Fe-deficient plant, as an example, would drive mineral weathering processes in the rhizosphere, also through exudation of organic ligands [10]. Because P and Fe are tightly bound in soil, plants have developed various physiological strategies to manage their limited availability.

To acquire poorly bioavailable Fe in the soil, non-gramineous plants, such as soybean, use a reduction-based mechanism (strategy-I), which involves excretion of protons from the roots to the rhizosphere, reduction of Fe^{3+} to the more soluble ferrous Fe (Fe^{2+}), and the transport of the ferrous ion across the root cell-membrane by the iron-regulated transporter (IRT) [11].

Reduced carbon substances released by roots of soybeans also promote microorganism redox processes [12], forming complexes with Fe and Al, and dissolving P from the surfaces of oxides [13, 14]. The acidification of rhizosphere by P-deficient plants is well documented in many studies [15, 16]. These processes transform crystalline Fe and Al oxides into water-soluble forms and then produce short-range ordered Fe-Al hydroxides through hydrolysis in wet and dry cycles [17]. However, the release of substances in the rhizosphere involves carbon costs related to both P and Fe acquisition by plants [18].

In annual plant species, it is estimated that 30–60% of photosynthetically fixed carbon is translocated to the roots, and a large proportion of that carbon (up to 70%) can be released into the rhizosphere [19]. During one vegetation period, cereals and grasses may allocate approximately 1500 to 2200 kg C ha^{-1} below ground [20]. Therefore, ensuring that Fe is found in short-range-ordered (SRO) form [21] could potentially reduce the costs associated with acquiring Fe and P.

The rhizosphere actively enhances mineral dissolution by altering the soil environment, mediating the uptake and release of elements, exuding organic compounds, and stimulating microbial growth [23]. When silicate rock powders—such as biotite schist—are added to soil, bioweathering processes promote the oxidation of Mn^{2+} and Fe^{2+} within mineral structures [22]. This oxidation is mechanistically coupled to the release of K from mineral interlayers, occurring either in solution or within the crystal lattice, driven by the diffusion of electron acceptors at the mineral surface [23]. The resulting structural oxidation generates a surplus of positive charge in the octahedral layer, destabilizing the mineral and facilitating K leaching [23]. Furthermore, the oxidation of Mn^{2+} and Fe^{2+} supplies electrons to soil microorganisms [24, 25], reducing the need for plants to expend carbon through organic acid exudation for the acquisition of Fe, Mn, and P [24, 25, 18]. This process also creates new surfaces for P adsorption, potentially improving nutrient availability in the soil [26].

Oxidized Fe released from the biotite structure during weathering initially forms short-range ordered or nanocrystalline phases in the soil [27]. The Fe(III) produced in this process reorganizes into SRO minerals, such as ferrihydrite, which possess a high specific surface area (SSA) [7]. These SRO Fe phases provide abundant new surfaces with a strong affinity for P adsorption [28–30]. Covering many soil surfaces, SRO minerals can reach surface areas of 348 m^2 g^{-1} [31] and exhibit high P adsorption capacity (up to 1068 μmol g^{-1} [31, 32]). The adsorption of P onto SRO Fe^{3+}-mineral surfaces limits the re-adsorption of P onto crystalline Fe^{3+} and Al^{3+} surfaces [7], potentially enhancing P availability to plants. Phosphorus bound to short-range ordered SRO minerals is particularly sensitive to redox oscillations due to the high reactivity of these iron phases [33]. Short-range-ordered Fe formed from biotite schist bioweathering is redox-sensitive, indicating that Fe-redox reactions occurring in the rhizosphere play a critical role in regulating soil P cycling [34, 35].

During the bioweathering of biotite schist, the rates at which Fe and K are released into the soil remain unknown. Although K derived from biotite schist is recognized as a slow-release source, most of this element remains structurally bound within mineral lattices [36] and is poorly detected by routine extractants such as Mehlich-1. In contrast, the fate of Fe released from K-bearing silicate rocks during bioweathering has received far less attention. It is unclear how this Fe reorganizes into SRO phases in tropical soils and how such transformations influence P retention, chemical extractability, and plant uptake under agricultural conditions.

The present study evaluated soybean growth in a Cerrado Oxisol amended with biotite schist as a source of K and Fe, in combination with other essential nutrients and a soluble P source. Specifically, we aimed to quantify K release over time and to assess whether Fe released during biotite bioweathering, through the formation of SRO Fe phases, alters soil P chemical extractability and P uptake by plants. By linking mineral weathering processes to soil P dynamics and crop nutrition, this study addresses a critical gap in understanding the mechanisms by which silicate rock amendments may improve phosphorus use efficiency in highly weathered tropical soils.

2 Materials and methods

2.1 Soil characterization

A composite soil sample (dystrophic Rhodic Haplustox [37]/*Latossolo Vermelho distrófico* [38], located at 15°35’38"S 47°44’12"W, in Planaltina, Federal District, Brazil, from 0 to 20 cm depth was collected. The soil analysis presented the following characteristics [39]: sand = 500 g kg^{-1}; silt = 75 g kg^{-1}; clay = 425 g kg^{-1}; organic matter = 20.6 g kg^{-1}; pHwater = 4.5 (using 10 g soil to 25 mL water suspensions); extracted by Mehlich-1 (HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}), 1:10 soil: solution ratio [40]: P = 3.7 mg dm^{-3} and K = 0.11 $cmol_c$ dm^{-3}; S extracted by $Ca(H_2PO_4)_2$ 0.01 mol L^{-1}, 1:10 soil: solution ratio [41], 15 mg dm^{-3}; by KCl (1 mol L^{-1}), 1:10 soil: solution ratio [39]: Ca = 0.4 $cmol_c$ dm^{-3}, Mg = 0.1 $cmol_c$ dm^{-3} and Al 1.1 $cmol_c$ dm^{-3}; H + Al extracted by $Ca(OAc)_2$ 0.5 mol L^{-1}, pH 7.0 [39] = 5.0 $cmol_c$ dm^{-3}; CEC at pH 7.0 = 5.6 $cmol_c$ dm^{-3}; B (hot water) = 0.52 mg dm^{-3}; micronutrients extracted by Mehlich-1: Fe = 90.9 mg dm^{-3}, Cu = 1.33 mg dm^{-3}, and Zn = 2.35 mg dm^{-3}; Mn = 3.6 mg dm^{-3}.

2.2 Rock characterization

Biotite schist in powdered form was collected from residue piles at a quarry in the State of Goiás, Brazil [42, 43]. Samples were air-dried and homogenized using the cone-and-quartering reduction method, forming the bulk sample. The sample passed through a 2 mm mesh sieve. Particle size distribution was (mm): <53 = 21.1%; 53–300 = 17.4%; 300–1000 = 2.4%, and 1000–2000 = 59.1%. Biotite schist chemical and mineralogical composition was published elsewhere [44]. The magnetic susceptibility of the biotite schist was measured at 12 m^3 kg^{-1}.

2.3 Experimental design

The experiment was carried out in a greenhouse at Embrapa Cerrados, Planaltina, Distrito Federal – Brazil. Sixty-four pots with 4 kg of air-dried, sieved, and homogenized soil were used in the experiment. Of these, 32 were treated with biotite schist (40 g per pot, representing 1% of the total soil mass). The application of 40 g of biotite schist (3.19% total K_2O [44, 22]) per pot adds a total of 1059.2 mg of K (equivalent to 264.8 mg K kg^{-1} of soil [23, 27, 45]). However, considering only the theoretical ‘available’ K contained in the most reactive mineral (biotite, which represents 11.2% of the rock [27, 45, 46], and K_2O content in the mineral biotite is ~9,0% [47]), it adds 334.7 mg of K per pot, or 83.7 mg K kg^{-1}. The selected biotite schist dose was not intended to provide the necessary amount of K for plant growth but was provided in excess to observe P and biotite schist interactions and P availability to plants. Therefore, vegetative biomass in this short-term greenhouse study does not represent final grain yield or commercial economic performance. Each pot was incubated for 90 days and watered weekly with deionized water to maintain soil moisture at about 70% of field capacity. To keep moisture levels steady, pots were weakly weighed, and water was added as needed by comparing saturated and dry soil weights. This approach was used throughout all incubation periods and during plant growth.

The soil, after incubation with 1% biotite schist for 90 days, presented the following chemical characteristics: pHwater = 4.6; P = 3.7 mg dm^{-3} and K = 0.40 $cmol_c$ dm^{-3}; S = 15.3 mg dm^{-3}; Ca = 0.4 $cmol_c$ dm^{-3}, Mg = 0.2 $cmol_c$ dm^{-3} and Al = 1.2 $cmol_c$ dm^{-3};

$H + Al = 5.8$ $cmol_c\ dm^{-3}$; CEC at pH 7.0 = 6.8 $cmol_c\ dm^{-3}$; B (hot water) = 0.43 mg dm^{-3}; Fe = 157.8 mg dm^{-3}, Cu = 1.33 mg dm^{-3}, Zn = 3.24 mg dm^{-3}; and Mn = 3.2 mg dm^{-3}.

Following the initial incubation period, the pots were allowed to air-dry. The soil was then incubated for an additional 30 days after being thoroughly mixed with a calcium carbonate and magnesium oxide blend in a 3:1 ratio (Ca:Mg, as $CaCO_3$ and MgO), to adjust the pH to 5.5. To estimate the amount of the 3:1 Ca:Mg mixture needed to adjust pot soils to the pH 5.5, ten grams of soil of each pot (80 g in total for each treatment) was collected to perform pH neutralization curves in laboratory. Increasing rates (0, 5, 10, 15, and 30 mg) of the Ca:Mg mixture was added to 10 g of the collected soil and mixed in 25 mL of water, with 3 replicates. These soil samples were incubated for 72-h before pH measurements were taken [44]. After the neutralization curves were determined, calculated doses of the 3:1 Ca:Mg mixture were mixed into the soil to equalize soil pH at 5.5 in all pots. After the 30 days incubation period, values of pH were measured to ensure the pH 5.5 was attained. Thereafter, treated soils in pots were allowed to dry for 7 days (Table 1).

After the incubation periods, the soil was allowed to dry and then received additional KCl treatments, which were thoroughly mixed. Of the 64 pots in total, 16 served as untreated controls, while another 16 received 150 mg K kg^{-1} as KCl (1,144 mg KCl per pot), referred to as the KCl treatment (KCl-T). Among the 32 pots previously incubated with biotite schist (1% w/w), 16 did not receive any further treatment (biotite schist only treatment, BSO), and the remaining 16 were treated with an additional 150 mg K kg^{-1} (BS + KCl treatment).

Subsequently, all 64 pots were fertilized with 2831 mg $(NH_4)_2SO_4$ pot^{-1}, 1643 mg $MgSO_4$ pot^{-1}, 1510 mg $Ca(H_2PO_4)_2$ pot^{-1}, and 200 mg trace element fertilizer FTE-BR10 (a fritted micronutrient fertilizer containing 2.5% B, 1.0 Cu, 4% Mn, 0.1% Mo, 4% Fe, 7% Zn and 0.1% Co) pot^{-1}. After thoroughly mixing fertilizers into the soil, the soils were incubated for 30 days to facilitate fertilizer reactions, primarily involving phosphorus on soil particle surfaces.

After the three incubation periods, the soil was sown with six soybean seeds (*Glycine max* L., cultivar BRS 7582) obtained from Embrapa Cerrados (Empresa Brasileira de Pesquisa Agropecuária – Embrapa Cerrados, Planaltina, Distrito Federal, Brazil; 15°35’38"S, 47°44’12"W). The seeds were certified, commercially available, and supplied for research use. All plants were grown under controlled greenhouse conditions at Embrapa Cerrados. Five days after emergence, only one plant was kept per pot. The experiment was evaluated at 17, 27, 37, and 47 days after planting.

The experimental design was completely randomized in a factorial scheme 4 × 4, with four replications and four treatments (relating to the K sources added) and four evaluation periods (17, 27, 37 and 47 days). At the end of each period, 16 pots were dismantled, and shoots, roots and soil were collected for analysis.

Table 1 Incubation-pH of soil, and soil mixed with 1% biotite schist

Treatment	**Equation** **mg kg^{-1}**	**R^2** **mg kg^{-1}**	**$CaCO_3$:MgO[a]** **mg kg^{-1}**
Soil control	$y = -0.0054x^2 + 0.217x + 4.318$	0.99	650
Soil + Biotite schist	$y = -0.054x^2 + 0.2236x + 4.4244$	0.99	555

Soil and soil-mixed with biotite schist treated with levels of the 3:1 Ca: Mg mixture incubated for 30 days prior to pH measurement (*n* = 3)

[a] Amount of 3:1 Ca: Mg mixture added per pot to increase soil pH in water to 5.5

2.4 Soil and plant chemical procedures and statistical analysis of the data

Plant shoots collected in each period were cut at the soil level. Roots were separated from soil and stored for analysis. The harvested plants (shoots and roots) were dried at 60 °C until constant weight was achieved. All the oven-dried materials were weighed to obtain the dry matter mass. Next, shoots and roots were ground in a Willey-type mill equipped with a 40-mesh sieve, homogenized, and then stored in properly labeled polyethylene bags in a dry chamber until the plant material analyses were conducted.

The concentrations of Al, B, P, K, S, Ca, Mg, Cu, Fe, Mn, and Zn in the dry biomass of plant shoots and roots were determined after extraction using HNO_3:$HClO_4$ in a digestion block [39]. Elemental concentrations were subsequently determined using inductively coupled plasma-optical emission spectrometry (ICP-OES). Phosphorus content was determined by colorimetry, and S by turbidimetry [48].

After harvesting, treated soils collected from pots were analyzed for the following characteristics [39]: pHwater and pH$CaCl_2$: P, K Na^+, S, Ca^{2+}, Mg^{2+}, Al^{3+}, and Si; micronutrients Cu, Fe, Mn, and Zn; H + Al; CEC at pH 7.0 was calculated as the sum of K, Ca, Mg, and H + Al.

Extractions for the sequential fractionation of inorganic P on the soil were carried out in the following order [49, 50, Table 2]. In all steps, the samples were agitated at 150 rpm and, after each extraction, washed with a 1 mol L^{-1} NaCl solution to obtain the extracts. Phosphorus quantification was performed using ICP-OES (Thermo Scientific iCAP 6000 Series).

Soil oxalate-extractable contents of Fe (Fe_ox), Mn (Mn_ox), Si (Si_ox), and their bound P (P_ox) were analyzed. Changes in Fe_ox are indicative of shifts toward more short-range-ordered (SRO)/poorly crystalline Fe forms; however, oxalate extraction is not mineralogically specific and does not by itself confirm the formation of discrete SRO Fe minerals (e.g., ferrihydrite). The soil samples were macerated and passed through a mesh sieve with a size less than 0.2 mm. An aliquot of 0.5 g of the sample was then treated with 40 mL of ammonium acid oxalate solution at pH 3 [51]. This mixture was stirred for 4 h in the dark, followed by centrifugation for 10 min at 3000 rpm and subsequent filtration. The concentrations of Fe, Mn, and P were determined using ICP-OES.

Tests for normality and equal variance [52] were used prior to the analysis of variance (ANOVA). The experimental results were analyzed using ANOVA, followed by the Tukey method for multiple comparisons, with the significance level set at $\alpha = 0.05$. For variables evaluated as a function of time, such as dry matter production and nutrient accumulation in plant tissues, regression analyses were additionally performed to describe temporal trends and nutrient dynamics during soybean growth. Pearson's correlation analyses were conducted to assess the relationships between soil chemical attributes and nutrient concentrations or accumulation in plant tissues. The strength and significance of correlations were evaluated using corresponding p-values. Results are

Table 2 Sequential fractionation procedure for inorganic P in soil samples

Extractant	Conditions	*P* fraction
NH_4Cl	1 mol L^{-1}, 0.5 h	Soluble P
NH_4F	0.5 mol L^{-1}, pH 8.2, 1 h	Al-bound P
NaOH	0.1 mol L^{-1}, 17 h	Fe-bound P
H_2SO_4	0.25 mol L^{-1}, 1 h	Ca-bound P

also shown as mean (s), where s is the standard deviation. Calculations and statistical analysis were performed with R 4.5.2 [53].

3 Results and discussion

3.1 Dry matter production

Dry matter production of soybean shoots and roots during the cultivation periods showed statistical differences between the treatments only at 47 days after planting ($F = 33.41$; $p < 0.0001$; Fig. 1). In contrast, root dry matter did not differ significantly between treatments ($F = 1.49$; $p = 0.2664$; supplementary material). The KCl-T promoted greater shoot growth means, considering all evaluated periods, than the other treatments, presenting 9.0%, 11.9%, and 41.1% higher dry mass production compared to the BS + KCl, BSO, and control treatments, respectively. This difference can be attributed to the slow release of K from biotite.

The average increase in dry matter production among the treatments became evident after 17 days of cultivation, compared to the control. Additionally, at 47 days, productivity using KCl-T was 9.88%, 13.43%, and 69.66% higher than with BS + KCl, BSO, and the control, respectively. However, there were no significant differences in productivity between the KCl-T and BS + KCl.

3.2 Biotite schist and K availability

At 17 days after planting, there was significant differences in K concentration in shoots among treatments ($p = 0.0015$); a rapid K release from the KCl-T in the soil (Fig. 2), reaching an average of 150 mg dm^{-3} of K ($s = 6.9$), as extracted by Mehlich-1, increasing average shoot concentrations up to 8.9 g kg^{-1} of K ($s = 3.2$) in this treatment (Fig. 3).

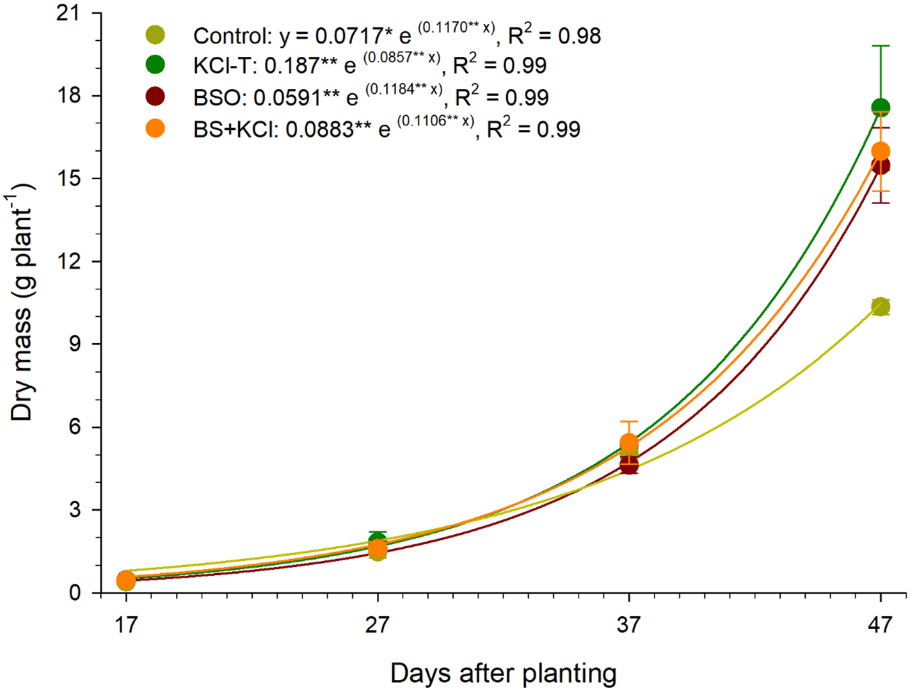

Fig. 1 Dry matter production of soybean shoots without potassium treatment (control), with KCl treatment (KCl-T), with biotite schist (BSO), and with biotite schist combined with KCl (BS + KCl). Error bars represent standard deviation ($n = 4$ per treatment; $n = 16$ per sampling time); * or ** denote statistically significant parameter estimates at $p < 0.05$ or $p < 0.01$, respectively

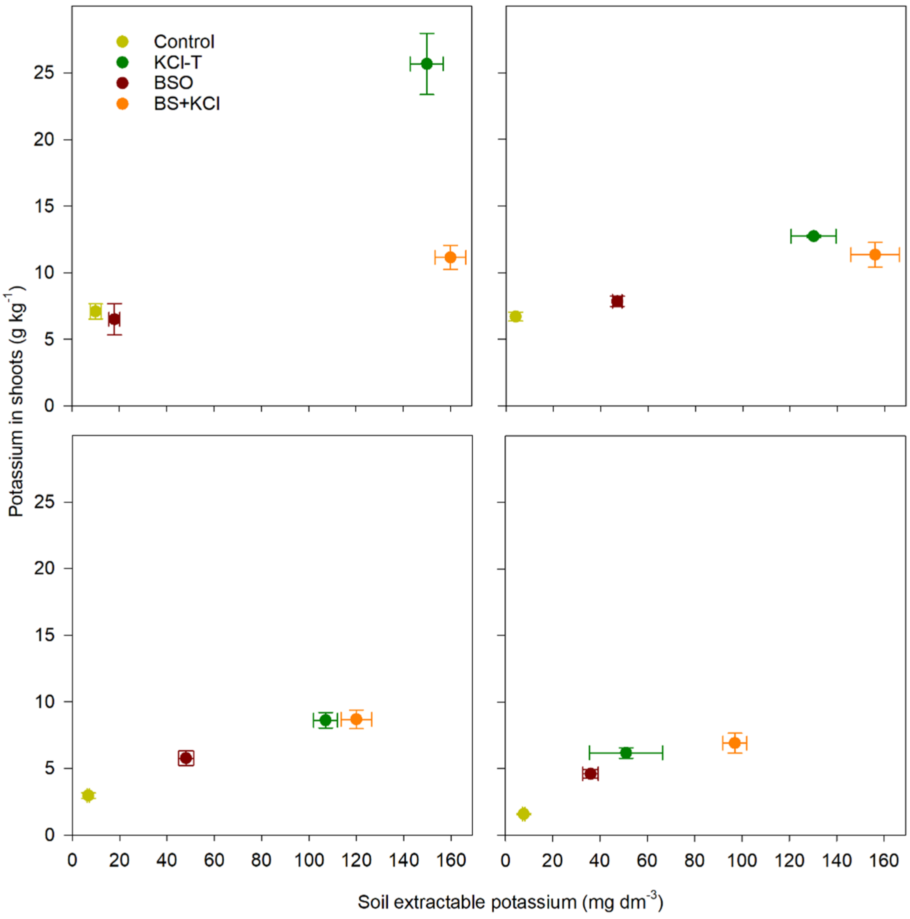

Fig. 2 Potassium concentration in shoots of soybean plants versus extractable potassium by Mehlich-1 in the soil at 17, 27, 37, and 47 days after planting under different potassium source treatments ($n = 4$); Error bars represent standard deviation ($n = 4$)

In the BSO, due to slow-release processes depending on bioweathering of fine particles, the soil K levels were much lower, resulting in lower initial K concentrations in plant tissues, similar to the control, with average K in shoots in the first 17 days after planting of 2.63 ($s = 0.37$) and 2.49 ($s = 1.16$) mg plant^{-1} of K, while Mehlich-1 K extractable was 10 ($s = 2.3$) and 18 ($s = 2.3$) mg dm^{-3} to control and with BSO, respectively (Fig. 2). The difference of 8 mg dm^{-3} between K released by BSO and control, even though small, may be attributed to the bioweathering of fine rock particles. It also seems that plants may struggle to acquire K from biotite schist in their initial growth stages as their growth was like control at 17 days after planting (Fig. 1).

Biotite is the only mineral reactive enough to release K into the soil in the short to medium term [45, 54]. The greater resistance of muscovite to release K compared with biotite is explained by its octahedral sites being fully occupied by Al, whereas biotite's octahedral sites contain Fe and Mg. Potassium in biotite can be accessible to crops, depending on the dosage, particle size, and soil biological activity [44]. When potassium from biotite is combined with an application of 150 mg K kg^{-1} as KCl, the resulting total potassium concentration notably surpasses what crops need. However, biotite schist releases K slowly.

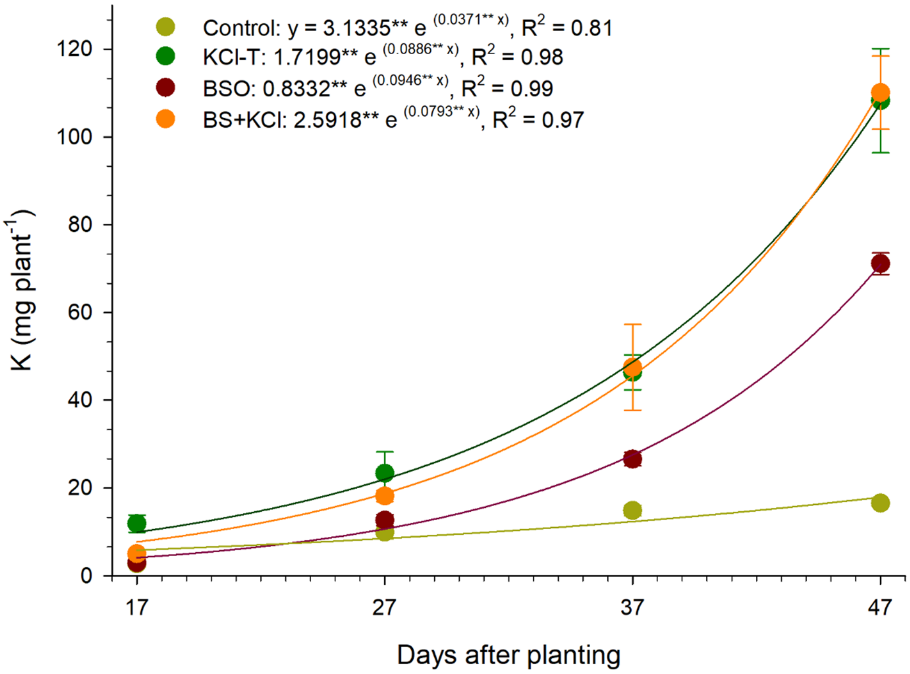

Fig. 3 Potassium accumulation in the shoots of soybean plants over the cultivation periods under different K source treatments. Error bars represent standard deviation ($n = 4$ per treatment; $n = 16$ per sampling time); ** denotes parameter significance at $p < 0.01$

The amount of K added by applying 1% biotite (BSO) was higher than that applied via KCl (KCl-T). Despite this, the Mehlich-1 extractant, the standard method for evaluating chemically extractable K in Brazilian soils, was unable to detect the K within the minerals (Fig. 2). Furthermore, K levels in the shoots of plants treated with BS + KCl were like those treated with KCl-T, at 27 ($p = 0.982$), 37 ($p = 0.999$), and 47 ($p = 0.944$) days after planting. Biotite schist only (BSO) showed potassium uptake levels between those of the control and KCl treatments.

At the end of the 47-day experiment, Mehlich-1 extraction showed higher residual K in the soil amended with BS + KCl than in the other treatments ($p < 0.001$). Potassium extracted by Mehlich-1 from the soil in the BSO jumped from 18 mg dm^{-3} at 17 days after planting to 47 ($s = 2$) mg dm^{-3} at 27 days after planting, likely due to bioweathering (Fig. 2). The Mehlich-extractable K concentrations from BSO remained steady throughout the experiment, while the K from KCl-T declined over time (Fig. 2). The bioweathering of biotite is intensified after plants grow, revealing the rhizosphere effects on biotite dissolution [23]. To a lesser extent, Mehlich-extractable K from the BS + KCl also declined with time (Fig. 2). Even though it appears that adding these two sources of K together may maintain available K levels (Fig. 3), potentially contributing to better plant nutrition over a longer term than either KCl-T or BSO, as observed in this experiment.

3.3 Biotite schist and P availability

Throughout the experiment, all plants, except for the control, Mehlich extracted similar amounts of P from the soil (Fig. 4). There was a strong correlation of 0.97 ($p < 0.001$) between P concentration in shoots and Mehlich-extractable P (Fig. 5). However, it's important to remember that this high correlation ($r = 0.97$) is derived from combining different treatments and time points. As a result, this relationship probably illustrates

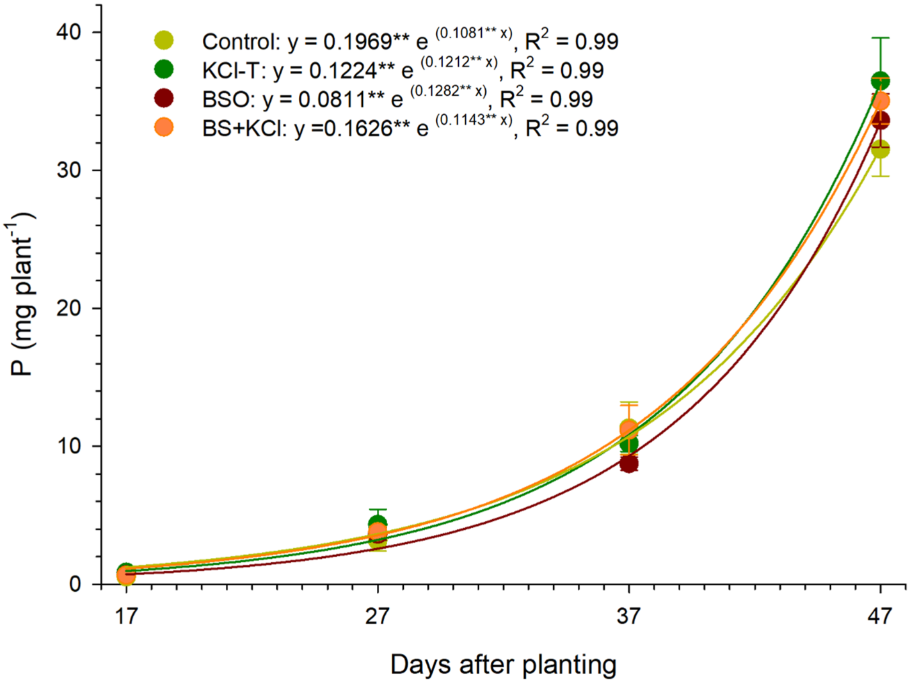

Fig. 4 Phosphorus accumulation in the shoots of soybean plants throughout the cultivation cycles under different treatments. Error bars represent standard deviation ($n = 4$ per treatment; $n = 16$ per sampling time); ** denotes parameter significance at $p < 0.01$

general depletion patterns during plant growth, rather than specific differences caused by individual treatments.

Significant differences for Mehlich-extracted P were observed at 17, 37, and 47 days ($p = 0.037$, 0.003, and < 0.0001, respectively), but not at 27 days across all periods evaluated. Along the time the average levels of P extracted from the soil by Mehlich-1 from all treatments decreased from the 17 (11.04 mg dm^{-3} of P; $s = 0.77$) to the 47 day after planting (8.95 mg dm^{-3} of P; $s = 1.03$; Fig. 5). After 47 days, Mehlich-extractable P was on average 22.63% higher in biotite (BSO and BS + KCl) treated samples than the non-treated (only KCl-T and control; Fig. 5). The BSO presented 19.06 and 24.9% more Mehlich-extractable P on the 47 day after planting than the KCl-T and the control.

Biotite schist has 0.2% P_2O_5 [23, 44], summing up to 9 mg P kg^{-1} of soil added per pot. The difference among treatments may be due to Mehlich-1 solubilizing P that is enclosed within minerals. Although the amount of P enclosed in the biotite schist is small compared to the added as triple superphosphate (100 mg P kg^{-1}) and, by its slow-release nature, it is not expected that it would change substantially the P balance. Several studies have demonstrated an increase in soil P concentrations with the application of silicate rock powders as extracted by 0.005 M H_2SO_4 [55], Mehlich-1 [56] or anion exchange resin [57], establishing the fundamental premise that silicate rock powder application increases chemically extractable P concentrations. However, when silicate rock powders are applied at high rates, the observed increase in extractable P is primarily attributed to changes in soil pH and competitive desorption mechanisms [57]. In previous studies, these effects were accentuated because soil pH was not standardized prior to treatment; in contrast, the present study controlled for pH, allowing for a more accurate assessment

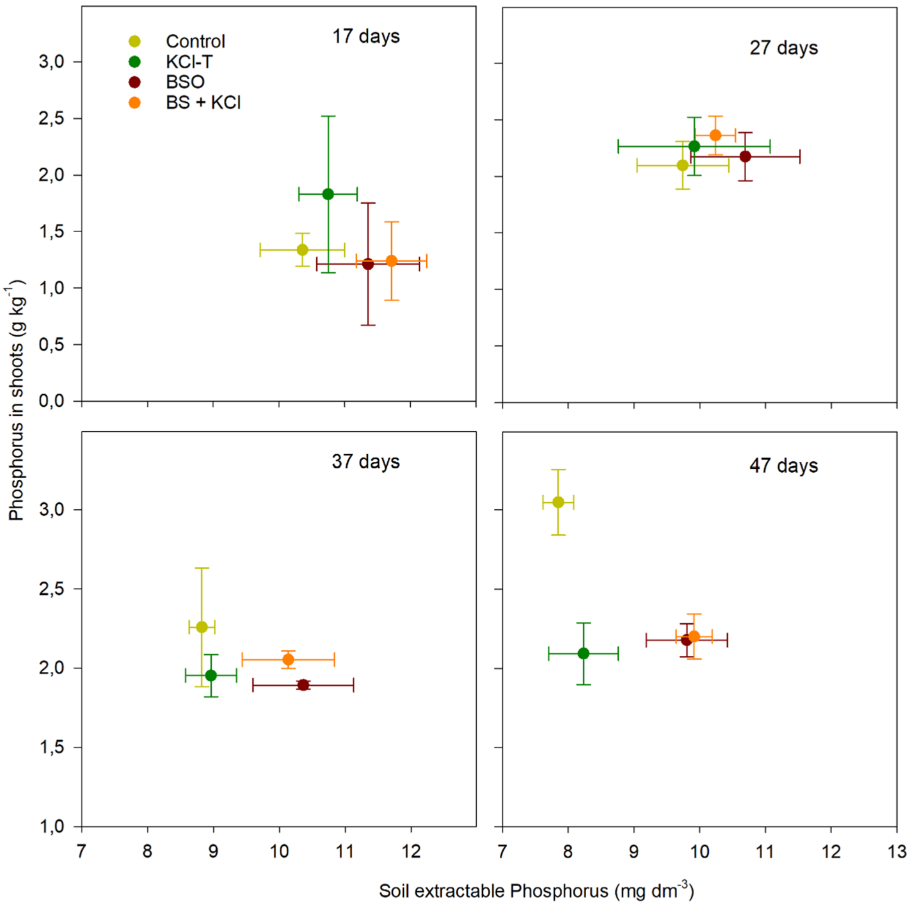

Fig. 5 Phosphorus concentration in shoots versus extractable P by Mehlich-1, in soybean plants at 17, 27, 37, and 47 days after planting under different K source treatments; Error bars represent standard deviation (*n* = 4 per treatment; *n* = 16 per sampling time)

of the direct effects of silicate application. A mechanism related to the adsorption of P into SRO Fe may be related to the increased extractability of P by Mehlich-1 (Fig. 6).

It was also observed that the P extracted from the soil by Mehlich-1 and by plants in all treatments (Figs. 4 and 5) was much lower than the P added (100 mg P kg^{-1}). This is attributed to the soil's adsorption capacity. Given that the pot experiment spanned approximately 5 months from the time P was mixed into the soil to the analysis, the reactions reducing P solubility continued over time. Using Mehlich-1 as the chemical extractant for all soil samples collected from the experiment (all treatments and all periods), resulted in a mean extracted value of 9.93 ($s = 1.16$, $n = 64$), consistent with published adsorption data for oxidic soils (Fig. 5) [58].

3.4 Iron and P availability

Plants under the KCl-T take up Fe from the soil's available pool, while both treatments involving biotite schist (BSO and BS + KCl) contributed additional Fe to the soil (Figs. 6 and 7). After 47 days, Fe accumulation in shoots was significantly higher in BS + KCl compared to other treatments ($p < 0.0001$; Fig. 6). The Fe uptake, at 37 days ($p = 0.0018$) and 47 days ($p < 0.0001$), showed significant differences among treatments. The Mehlich-extractable Fe concentration in the studied soil was 90.9 mg dm^{-3}, while the average level of Mehlich-1 extractable Fe in Cerrado soils is 32.5 mg dm^{-3}, ranging from 3.7 to

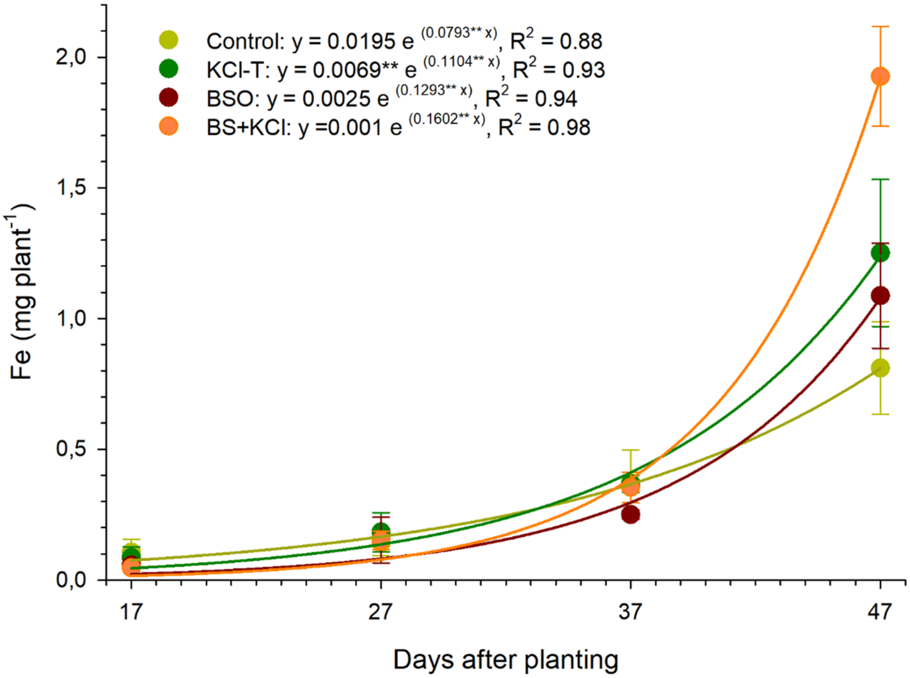

Fig. 6 Iron accumulation in the shoots of soybean plants throughout the cultivation cycles under different treatments. Error bars represent standard deviation ($n = 4$ per treatment; $n = 16$ per sampling time); ** denotes parameter significance at $p < 0.01$

74.0 mg dm^{-3} of Fe [5]. For the KCl-T, the Mehlich-extractable Fe pool decreased from 94.6 (s = 14.5) to 67.3 (s = 1.5) mg dm^{-3}, when comparing 17 and 47 days after planting. In contrast, for the BSO, the Mehlich-extractable Fe pool increased from 92.6 (s = 10.5) to 137.2 (s = 18.5) mg dm^{-3} (Fig. 7).

The solubility of crystalline Fe minerals in soil is usually very low [29]. Consequently, Fe mobilized from the Mehlich-extractable pool — including soluble forms and, to some extent, SRO Fe — was deposited in the roots (dataset in the supplementary material), with a portion translocated to the shoots (Fig. 6). Despite the increase in Mehlich-extractable-Fe from soil in BSO, likely due to mineral dissolution (Fig. 7), it did not result in more Fe in plant tissue up to 47 days after planting (Fig. 6). This may be due to the low availability of K in the soil during the initial growth of plants in BSO (Fig. 3).

At 17 and 27 days of growth, Mehlich-extractable Fe did not differ among treatments, only after 37 (p-value = 0.001) and 47 (p-value < 0.0001) days where BSO and BS + KCl presented 30 and 41.6% more Mehlich-extractable Fe, respectively, than the KCl-T and control (Fig. 7).

Soil-extracted Fe and P, as determined by Mehlich-1, exhibited treatment-dependent co-variation ($r = 0.39$; $p = 0.0015$; all periods)—most notably at 37 ($r = 0.68$; $p = 0.003$) and 47 ($r = 0.70$; $p = 0.002$) days after planting (Fig. 7)—distinctly separating biotite schist treatments from both the KCl-T and control groups. Despite persistent differences in Mehlich-extractable P and Fe, after 47 days, P uptake by plants was similar among all treatments except the control (Fig. 4). In the treatments amended with biotite schist (BSO and BS + KCl), after 47 days, P extractability by Mehlich-1 was on average 22.63% higher than in the non-amended treatments ($p < 0.0001$). In contrast, in the KCl-T and control treatments, a larger fraction of soil P remained in pools with lower Mehlich-1

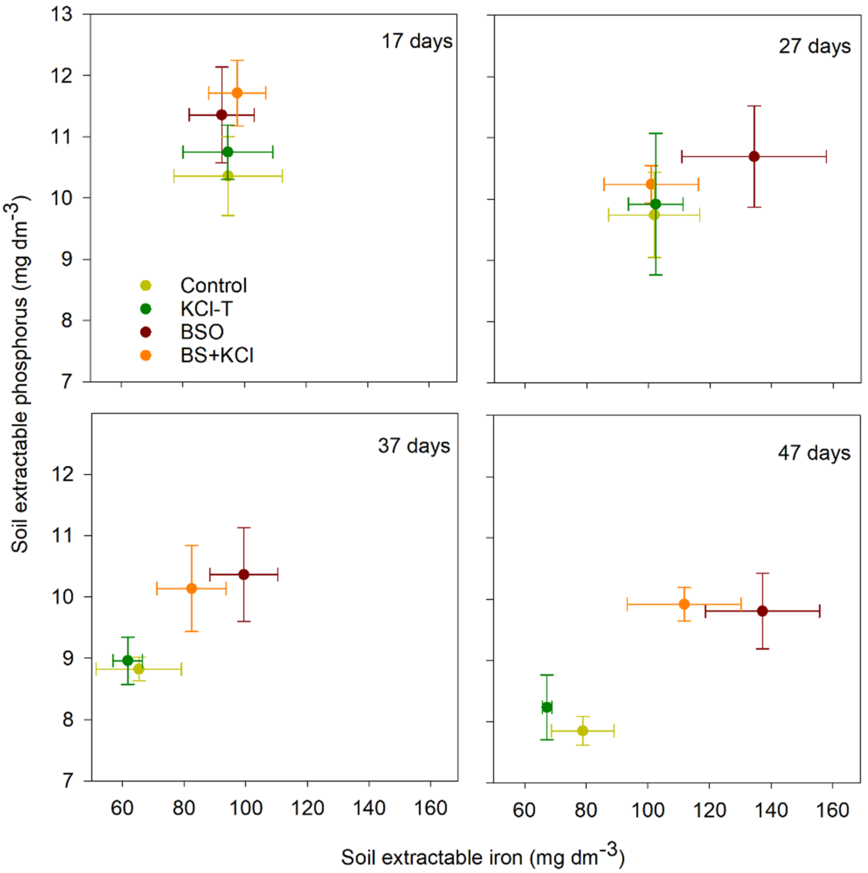

Fig. 7 Mehlich-extractable P as a function of Mehlich-extractable Fe in soybean plants at 17, 27, 37, and 47 days post-planting across various potassium source treatments. Error bars indicate standard deviation (*n* = 4 per treatment; *n* = 16 per sampling interval)

extractability, commonly associated with crystalline Fe oxides and Al forms in highly weathered soils.

The increase in Mehlich-extractable Fe observed in the biotite schist treatments suggests a possible contribution of Fe released during mineral dissolution. Iron released from silicate minerals is known to reorganize into SRO Fe phases under soil conditions, which provide a high density of reactive surface sites for phosphate retention [7]. The solubility of Fe^{3+} oxides decrease in the following order: $Fe(OH)_3$ (SRO) > $Fe(OH)_3$ (soil) > Fe_2O_3 (maghemite) > FeOOH (lepidocrocite) > Fe_2O_3 (hematite) > FeOOH (goethite) [7]. Accordingly, soils enriched in SRO Fe phases tend to exhibit higher chemical extractability of P compared with soils dominated by more crystalline Fe and Al oxides [33].

A field study conducted in a Typic Haplustox (Latossolo Vermelho-Amarelo Ácrico) from Goiás, Brazil, showed that Fe application rates of up to 400 kg ha^{-1} as $FeSO_4$ did not increase common bean yield [7]. That study did not evaluate temporal changes in soil Fe and P pools and did not account for soil acidification associated with Fe(II) oxidation [59]. Because $FeSO_4$ additions promote proton release during oxidation, liming is required to maintain soil pH at agronomically suitable levels. In addition, the dissolution of crystalline Fe oxides is enhanced by higher contents and lability of organic matter, which favor the formation of SRO Fe phases [29]. Under conditions of high organic

Table 3 Means of Fe, Mn, and P content, as extracted by ammonium oxalate, in soils cultivated with soybean plants at 17, 27, 37, and 47 days after planting under various K source treatments

Time (days)	**Fe** **mg kg^{-1}**	**Mn** **mg kg^{-1}**	***P*** **mg kg^{-1}**
17	1440 a	8425 a	83.0 a
27	1454 a	8735 a	80.7 ab
37	1290 b	7810 b	74.7 b
47	1266 b	8420 ab	68.7 b
ANOVA (F)	12.84	9.41	4.02
p-value	< 0.0001	0.0002	0.012

Means followed by the same uppercase letter within each treatment across cultivation periods do not differ statistically according to Tukey`s test (α < 0.05)

matter and elevated SRO Fe contents, the marginal effect of additional Fe inputs on P availability is therefore expected to be limited.

The sequential fractionation of inorganic phosphorus (Pi) in the soil showed statistically similar results for P bound to Al, Ca and Fe in all treatments, with values 35.59 ($s = 4.82$; $p = 0.40$), 20.63 ($s = 5.61$; $p = 0.06$), and 58.78 ($s = 14.36$; $p = 0.10$) mg P kg^{-1} in the soil.

The temporal patterns observed for Fe_ox, Mn_ox and P_ox reveal a significant effect of time on all three elements, indicating that the progression of the experiment strongly influenced element availability (Table 3). Nutrient concentrations declined over time, with Fe_ox vs. Mn_ox ($r = 0.45$, $p = 0.0002$) and Fe_ox vs. P_ox ($r = 0.61$, $p < 0.0001$) showing significant correlations. Root-induced rhizosphere processes, aside from biotite participation, can play a significant role in enhancing plant nutrient uptake from soil, thereby leading to a gradual reduction in soil nutrient content over time.

Despite the increased Mehlich-extractable P observed in biotite-amended soils, soybean P uptake did not differ from the KCl-T at 47 days, indicating that biotite schist primarily induced redistribution of P among soil pools—particularly those associated with SRO Fe—without increasing short-term plant P availability. Short-range ordered Fe acts as a strong sink for P, it is also highly sensitive to biological mobilization strategies, such as reductive dissolution or organic acid exudation [13, 14]. We propose that further applications of the crushed rock could lead to a buildup of SRO in the soil, potentially causing significant changes in P availability and legacy. This is critical because SRO Fe minerals, such as ferrihydrite, possess a high specific surface area and are the primary sorbents for phosphate in highly weathered soils [33].

Therefore, we hypothesize that a fraction of the P associated with SRO could be accessible for plant uptake. However, care must be taken regarding the long-term legacy of this fraction, as SRO Fe can transform into crystalline oxides during redox oscillations, potentially occluding P and reducing its future accessibility [26].

4 Conclusions

This study examined soybean growth in Cerrado soils amended with biotite schist as a source of K and Fe, supplemented by additional essential nutrients and a soluble P source. Findings point to the possibility that K and Fe are gradually released from biotite schist through bioweathering processes. Soils amended with biotite schist exhibited higher Mehlich-extractable P at later sampling times within the duration of the experiment. The co-variation between Mehlich-extractable Fe and P suggests that Fe released during biotite bioweathering may have contributed to the formation of SRO Fe phases, which are known to strongly sorb phosphate. The long-term fate of P associated with SRO Fe remains uncertain, as these phases may either remain biologically accessible or transform into more crystalline forms that occlude P.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44378-026-00215-y.

Supplementary Material 1.

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Author contributions

G.M. conceived the study, designed the methodology, participated in conducting the experiments, and led the data interpretation and manuscript writing. L.L. contributed to methodology development, data analysis, and the writing of the manuscript. E.G. and P.C. assisted in methodology development, conducted laboratory analyses, and participated in both data interpretation and manuscript writing. E.M. performed the statistical analyses and contributed to data interpretation. J.C. assisted with the methodology design and the execution of the experiment. J.P. and É.S. contributed to the interpretation of results and critically revised the final version of the manuscript.

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Data availability

The dataset generated and analyzed during this study has been deposited in the Embrapa Redape repository. Permanent access will be provided at https://doi.org/10.48432/GNIJ1K once the study is published. During the peer review process, the dataset can be accessed using the temporary link: https://www.redape.dados.embrapa.br/dataset.xhtml? persistentId=doi:10.48432/GNIJ1K&version=DRAFT.

Declarations

Ethics approval and consent to participate

The soybean plants (Glycine max L. cultivar BRS 7582) utilized in this research were cultivated solely under controlled greenhouse conditions at Embrapa Cerrados, Planaltina, DF, Brazil. No wild plant material was collected for the study. All experimental procedures adhered strictly to Brazilian national guidelines governing the use of cultivated plant material in scientific research. Because the study exclusively used commercially available cultivated soybean seeds and did not involve endangered or protected species, there was no requirement for special permissions or licenses. This study did not involve human participants or the use of human data.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data in any form.

Competing interests

The authors declare no competing interests.

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