

Silicate rock remineralizers sustain soil potassium availability and irrigated rice yield in subtropical agroecosystems

Verônica Lemos Vargas

Federal University of Pelotas (UFPel)

Robson Bosa dos Reis

Federal University of Pelotas (UFPel)

Ezequiel Helbig Pasa

Federal University of Pelotas (UFPel)

Thais Vergara Costa

Federal University of Pelotas (UFPel)

Andrew dos Santos Otero

Federal University of Pelotas (UFPel)

Rogério Oliveira de Sousa

Federal University of Pelotas (UFPel)

Pablo Abelaira Souza

Federal University of Pelotas (UFPel)

Walkyria Bueno Scivittaro

Embrapa Clima Temperado

Edson Campanhola Bortoluzzi

Passo Fundo University

Filipe Selau Carlos

filipeselaucarlos@hotmail.com

Federal University of Pelotas (UFPel)

Research Article

Keywords: potassium fertilization, remineralizers, irrigated rice, soil potassium availability

Posted Date: September 17th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10778596/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Potassium (K) reserves in Brazilian soils are generally insufficient to meet the K requirements of irrigated rice, making nutrient replacement through mineral fertilization necessary. In Brazil and other tropical countries, potassium chloride (KCl), the main K source used in agriculture, is largely imported, increasing production costs and making food security more vulnerable. Therefore, the use of alternative K sources capable of replacing KCl represents a challenge for ensuring food security. This study aimed to evaluate irrigated rice performance in three major rice-producing subregions using remineralizers as K sources, compared with KCl. The field experiment consisted of six treatments: T1 - no K fertilization (control); T2 - KCl (conventional management); and alternative K sources: T3 - phonolite; T4 - syenite; T5 - nepheline syenite; and T6 - mica schist. The experiments were conducted at four sites in southern Brazil (Palma/Capão do Leão, RS; Granja 4 Irmãos/Rio Grande, RS; AUD/Camaquã, RS; and Capão Sementes/Camaquã, RS), all on Albaqualfs, during the 2023/24 growing season. Overall, the alternative sources increased soil exchangeable K concentrations (Mehlich-1) by 128%, increased plant height by 3%, and markedly improved the soil exchangeable K balance (> 100%) compared with KCl, while maintaining irrigated rice grain yield at levels similar to those obtained with the conventional fertilizer (~ 8.5 Mg ha⁻¹). The results demonstrate that alternative K sources can provide nutritional performance comparable to that of conventional fertilizer. Taken together, these findings highlight the potential of these sources as viable alternatives to conventional K fertilization in subtropical rice-growing systems, contributing to more resilient and sustainable agri-food systems.

Highlights

- Remineralizers increased soil exchangeable K by 128% compared with KCl.
- Rice yield remained similar to conventional K fertilization (~ 8.5 Mg ha).
- Remineralizers improved K balance and offer sustainable alternatives to KCl.

1. Introduction

Modern agriculture faces the challenge of reconciling the maintenance of long-term productivity with the conservation of agroecosystem stability and sustainability in the face of growing global food demand. In this context, some crops assume a strategic role in food and nutritional security. Among them, rice (*Oryza sativa* L.) stands out as one of the world's major staple foods, being fundamental to the supply of energy and nutrients and to the food security of billions of people.

Brazil is the leading rice producer outside the Asian continent, with production concentrated in the southern region of the country under continuously flooded irrigation systems (Ribas et al., 2025). Over the past 20 years, rice production systems in Brazil have nearly doubled their yields, reaching values above 8 Mg ha⁻¹ (Sousa et al., 2021; Ribas et al., 2021; Marques Neto et al., 2023). This progress has

resulted from the intensification of agricultural management, with greater use of inputs to sustain high yields, which, in turn, increases nutrient demand.

In this context, potassium (K) plays a critical role, particularly in high-yielding crops, which can remove more than 240 kg ha⁻¹ of K when grain yields (GY) reach 10–12 Mg ha⁻¹. Therefore, replenishment of K, regardless of its source, is essential to sustain crop productivity and soil fertility, given its fundamental role in a wide range of biochemical and physiological processes involved in plant growth, development, and metabolism (Johnson et al., 2022; Sardans and Peñuelas, 2021).

However, the hydromorphic soils of southern Brazil are mostly derived from sediments, have a low cation exchange capacity (CEC), and exhibit low K availability in readily available forms (Boeni et al., 2010), which may compromise the long-term supply of this nutrient to plants. Consequently, highly productive agricultural systems become dependent on K replenishment through mineral fertilization.

In this context, approximately 80% of the fertilizers used in Brazilian agriculture are imported (ANDA, 2019; Farias et al., 2020), making agricultural production systems dependent on the international market. The supply of KCl is one example, with costs having increased significantly (CNA, 2024). In addition, the use of soluble fertilizers such as KCl is associated with relevant environmental impacts, reinforcing the need for more sustainable nutrient management strategies (Geilfus, 2019).

In this context, K present in silicate rocks has potential for alternative use, provided that the rocks are applied in ground form. Rock powders, also referred to as remineralizers under Brazilian legislation, are gaining recognition as a promising alternative. These rocks, often derived from mining activities, can be subjected to simple physical processing and applied to the soil to supply nutrients such as calcium (Ca), magnesium (Mg), phosphorus (P), and K (Manning et al., 2020; Ramos et al., 2022), as well as micronutrients (Chaudhary et al., 2011), while also contributing to the correction of soil acidity and increasing cation exchange capacity (CEC) (Brasil, 2016; Basak et al., 2019; Swoboda et al., 2022; Daniell and Tonder, 2023; Wang et al., 2024). Additionally, their use may reduce dependence on imported inputs, promote the valorization of industrial by-products, and potentially contribute to atmospheric CO₂ sequestration (Strefer et al., 2018; Beerling et al., 2020).

Although studies have reported positive effects of remineralizers on the yield-related attributes of different crops (Reis et al., 2024; Ramos et al., 2022), most have been conducted under controlled or protected-environment conditions. Field studies evaluating rock powders as an alternative source of K for grain crops remain scarce, particularly for irrigated rice in southern Brazil. This knowledge gap becomes even more evident when considering the relationship among K dynamics in the soil, plant uptake, and the productive efficiency of agricultural systems.

Therefore, the objective of this study was to evaluate alternative K sources through the application of four silicate rock powders (phonolite, syenite, nepheline syenite, and mica schist) in comparison with KCl, with respect to soil K fractions, plant nutritional status, and irrigated rice yield. To this end, K concentrations in the soil and plant biomass, plant height, chlorophyll index, and GY were evaluated at

four production sites representative of the main rice-growing region of Brazil. We hypothesized that the use of rock powder as a K source could replace conventional KCl fertilization while maintaining crop productivity and nutritional performance and contributing to more sustainable production systems.

2. Materials and methods

2.1. Site description

The experiment was conducted during the 2023/24 growing season under field conditions in southern Brazil, the country's main rice-producing region, at four sites: L1) Centro Agropecuário da Palma - Experimental Station of the Federal University of Pelotas, in Capão do Leão, Rio Grande do Sul, Brazil (31° 46' 3" S, 52° 26' 55" W); L2) Granja 4 Irmãos, Rio Grande, Rio Grande do Sul, Brazil (32° 1' 60" S, 52° 5' 55" W); L3) AUD/IRGA Experimental Station; and L4) Sementes Capão Grande, both located in Camaquã, Rio Grande do Sul, Brazil (30° 51' 5" S, 51° 48' 46" W) (Fig. 1). All sites have a warm and humid summer climate, classified as Cfa according to Köppen (Wrege et al., 2011), and the soil is classified as Albaqualf (USDA, 2014). The chemical characterization of the Albaqualfs at the four study sites is presented in Table 1.

2.2 Experimental Design and Conducting the Experiment

The experiment consisted of different potassium fertilization treatments in rice. The treatments included: T1 - no potassium fertilization (control); T2 - potassium chloride (KCl) (conventional management); T3 - phonolite; T4 - syenite; T5 - nepheline syenite; and T6 - mica schist. The experiment was conducted in a randomized complete block design with four replications. The experimental units consisted of plots measuring 3.4 m in width and 8 m in length, totaling 27.2 m².

Treatment rates were determined according to the official recommendations for irrigated rice, based on the soil K concentrations obtained from the chemical characterization conducted prior to the beginning of the experiment, which varied among the study sites (CQFS-RS/SC, 2016). Based on the recommended K rates, the amounts required for each treatment to meet the potassium fertilization demand were calculated according to the total K content (%) of each mineral. A detailed description of the treatments used, including total K content (%) and the K application rates, is provided in Table 2.

For the treatments with silicate minerals (T3, T4, T5, and T6), remineralizer rates were applied at an amount equivalent to three times the recommended rate, based on the total K content. This approach was adopted due to the low solubility and gradual release of K from these materials (< 1% water-soluble), in contrast to the high availability of K supplied by KCl (100% water-soluble) (Manning, 2010; Harley & Gilkes, 2000).

The timing of treatment application differed among the sources: KCl was applied when 50% of the plants had reached the V4 developmental stage (Counce et al., 2000), whereas the silicate materials were incorporated approximately 15 days before the sowing of the winter cover crop, with the aim of

extending the period of interaction with the soil and promoting weathering processes and nutrient cycling.

In all treatments, a winter cover crop of Persian clover was previously established, sown during the first half of April of the 2023 growing season, using the PGW Lightning cultivar at a seed rate of 5 kg ha^{-1} , with 0.17 m row spacing and an application of 75 kg ha^{-1} of P_2O_5 . Prior to rice sowing, the Persian clover was managed with two chemical herbicide applications, at 40 and 25 days before sowing, respectively: the first with glyphosate + 2,4-D and the second with glyphosate + metsulfuron-methyl.

Irrigated rice was sown during the first half of October 2023, using the IRGA 424 RI cultivar, with 0.17 m row spacing and a seed rate of 100 kg ha^{-1} . Basal fertilization consisted of 80 kg ha^{-1} of P_2O_5 and 150 kg ha^{-1} of N, applied in the planting row and as a surface application, respectively (67% of the dose at the V3 stage and 33% at the end of the vegetative period, V9/R0) (CQFS-RS/SC, 2016; SOSBAI, 2025). Urea (45-00-00) and MAP (11-52-00) were used as fertilizer sources to meet N and P requirements, respectively. Rice pest and disease management was carried out according to SOSBAI (2025). Irrigation consisted of maintaining a continuous water layer of 5–10 cm once the plants reached the V3 phenological stage (onset of tillering), which was maintained until 10 days before harvest.

2.3 Soil and Aboveground Biomass Sampling

Soil samples were collected in early November 2023, 20 days after sowing the 2023–2024 summer crop. Eight samples were collected from each experimental unit at a depth of 0–0.20 m. The soil was dried in a forced-air circulation oven at 40–45°C, and larger clods were broken up, ground, and sieved ($\varnothing = 2.0 \text{ mm}$) (TEDESCO et al., 1995). To quantify nutrients in the aboveground biomass (AGB), samples were collected from the rice crop when it reached full maturity (SOSBAI, 2025). Three random samples were collected from each experimental unit using a $0.25 \times 0.25 \text{ m}^2$ metal frame, corresponding to the aboveground portion of plants cut at ground level. The samples were subsequently dried at 60°C and ground to pass through a 2-mm sieve.

2.4 Assessments

2.4.1 Soil K Fractions

The K fractions evaluated in this study were exchangeable K and total K (K_{total}). Exchangeable K was estimated using two chemical extractants: (a) Mehlich-1 ($K_{\text{exch-M}}$), consisting of a mixture of diluted strong acids: 0.05 mol L^{-1} hydrochloric acid (HCl) and $0.0125 \text{ mol L}^{-1}$ sulfuric acid (H_2SO_4); and (b) ammonium acetate ($K_{\text{exch-AA}}$), a solution prepared with 1.0 mol L^{-1} ammonium acetate ($\text{CH}_3\text{COONH}_4$) adjusted to pH 7.0. For both methods, extractions were performed using a soil-to-solution ratio of 1:10, with a contact time of 16 h under constant shaking. Exchangeable K in the extracts was quantified by flame emission spectrophotometry, according to the methodology described by Tedesco et al. (1995). K_{total} was determined by X-ray fluorescence spectroscopy (XRF), using pellets prepared at a sample-to-wax ratio of X:Y and pressed at 20 tons for 3 min. The XRF configuration used was “EQUA_Oxides” in two

analytical modes: “Pellet WAX” and “Solid”. Analyses were performed using a BRUKER S2 Ranger XRF spectrometer.

2.4.2 X-ray Diffraction (XRD) - Mineralogical Composition of the Samples

The mineralogical composition of the clay fraction (0-0.2 m) was determined by X-ray diffraction (XRD). The samples were previously oven-dried at 45°C, ground, and sieved to a particle size of 400 mesh (0.025 mm). The analysis was performed using a non-oriented dry powder preparation. Approximately 3 g of each sample were placed in a specific XRD sample holder and carefully compacted to obtain a flat surface parallel to the edge of the holder. The analyses were conducted using a D2 PHASER diffractometer (Bruker), equipped with a Lynxeye™ fast linear detector and operated with CuK α radiation ($\lambda = 1.5418 \text{ \AA}$). The samples were scanned over a range of 4–50° (2 θ), with a step size of 0.02° (2 θ), a counting time of 0.500 s per step, and a total effective measurement time of 1650 s, resulting in analyses lasting approximately 30–40 min. The resulting diffractograms were processed using Diffrac.Suite™ and Diffrac EVA software, and mineral identification was performed by comparing peak positions and intensities with standards described by Brindley & Brown (1980), as well as with mineralogical databases (WebMineral, 2024; Mindat, 2024). The mineralogical composition was estimated directly by the software based on the probability of matching the diffracted peaks. Graphs and percentages of each constituent mineral were extracted from the processed data. Additional information is provided in Table S1 of the supplementary material.

2.4.3 Determination of N and K in Plant Biomass

To determine N and K concentrations, 0.2 g of the AGB samples were subjected to acid digestion (H₂SO₄) at high temperature to convert nutrients from organic to mineral forms. The N and K concentrations in the resulting extract were determined by the Kjeldahl distillation method and flame photometry, respectively (Tedesco et al., 1995).

2.4.4 Total Chlorophyll Index

The chlorophyll index was determined by measuring ten flag leaves at the central portion of the leaf when the rice plants reached the R2 phenological stage (panicle branch differentiation). Measurements were performed using a FALKER CFL 1030 chlorophyll meter. The device uses three light frequency bands to perform a detailed analysis of the leaf by measuring light absorption and estimating the chlorophyll content.

2.4.5 Grain Yield

At the end of the rice crop cycle, at the physiological maturity stage, GY was quantified by harvesting a useful area of 2 m × 2 m, totaling 4.00 m² in each experimental unit. After harvesting, the samples were properly identified and threshed. Subsequently, impurities were removed, and grain weight and moisture content were determined and used to calculate GY (Mg ha⁻¹) at 13% moisture content.

2.4.6 Soil K Balance

To calculate the K balance in the system (KB), all K inputs via fertilizers and K outputs via rice grains were quantified using the data presented in Table 2, based on the mean values across the study sites. K export (total K removal) through grain was calculated using the average K concentration of 2.5 kg Mg^{-1} for rice (CQFS-RS/SC, 2016). The KB was calculated according to Eq. 2:

$$KB_{system} = K_{input} - K_{output} \quad \text{Equation 2}$$

where:

KB_{system} = K balance in the system (kg ha^{-1})

K_{input} = total K input via fertilizer

K_{output} = total K output via grain export

The soil exchangeable KB was calculated as the difference between the final and initial exchangeable K contents extracted by Mehlich-1 (KB_{exchM}) in the 0-0.2 m soil layer (Eq. 3):

$$KB_{exch} = K_{exch_final} - K_{exch_initial} \quad \text{Equation 3}$$

KB_{exchM} = soil exchangeable K balance (kg ha^{-1})

K_{exchM_final} = final soil exchangeable K stock extracted by Mehlich-1 in 2024

$K_{exchM_initial}$ = initial soil exchangeable K stock extracted by Mehlich-1 in 2023

2.4.7 Statistical Analysis

The study data were assessed for normality using the Shapiro-Wilk test. After meeting the assumptions of normality, the variables were subjected to Tukey's test for mean comparison ($p < 0.05$). Statistical analyses were performed using the R® statistical software.

3 Results

3.1 Soil K Fractions

Soil K_{total} concentrations were not affected by the use of different potassium fertilization sources (Fig. 2a). At L1 and L2, K_{total} concentrations ranged from 17,000 to 18,000 and from 13,000 to 18,000 mg kg^{-1} , respectively. In comparison, at L3 and L4, the mean K_{total} concentrations were relatively higher, ranging from 46,000 to 47,000 and 23,000 mg kg^{-1} , respectively. Regarding K_{exch-M} , no differences among treatments were observed only at L1, where K concentrations ranged from 70.8 to 75.2 mg kg^{-1} (Fig. 2b). At L2 and L4, treatments T3, T4, and T6 significantly increased K_{exch-M}

concentrations compared with T1 and T2, with an average increase of 39.5 mg kg^{-1} (44.6%) at each site. In contrast, at L3, the application of both silicate minerals ($100.7\text{-}125.9 \text{ mg kg}^{-1}$) significantly increased $K_{\text{exch-M}}$ concentrations only compared with the control treatment (101 mg kg^{-1}), with no differences among the other treatments (Fig. 2b). $K_{\text{exch-AA}}$ concentrations varied among sites and did not follow a consistent pattern (Fig. 2c). At L1 and L4, $K_{\text{exch-AA}}$ concentrations ranged from 9 to 12.2 mg kg^{-1} and from 33 to 39 mg kg^{-1} , respectively; however, treatments did not differ at either site. Conversely, at L2, the highest $K_{\text{exch-AA}}$ concentrations were observed under T3 and T4, both showing significant mean increases of 22.2 mg kg^{-1} compared with the other treatments. Similarly, at L3, the highest $K_{\text{exch-AA}}$ concentration was observed under T4 (39 mg kg^{-1}), with significant mean increases compared with T5 (23 mg kg^{-1}) and T6 (21 mg kg^{-1}) (Fig. 2c).

3.2 Mineralogical Composition of Remineralizers and Potassium Sources

The mineralogical composition determined by X-ray diffraction (XRD) revealed variation in the mineral phases comprising each of the evaluated materials (Fig. 5). KCl exhibited sylvite as its sole mineral phase (Fig. 5a). Among the remineralizers used as alternative K sources, phonolite was characterized by the presence of alkali feldspars (sanidine and anorthoclase), microcline, and nepheline (Fig. 5b). The mica schist sample was predominantly composed of phyllosilicates (muscovite/biotite), with quartz and associated K-feldspar also present (Fig. 5c). Syenite was characterized by quartz as the predominant phase, accompanied by microcline, orthoclase, and albite (Fig. 5d). Finally, nepheline syenite contained alkali feldspar, microcline, nepheline, and residual quartz in its composition (Fig. 5e).

3.3 K and N Concentrations in Plant Biomass

Nitrogen (N) concentrations in the AGB did not differ significantly among treatments at any of the four study sites (Fig. 4a). Across the sites, N concentrations in the AGB were generally similar, ranging from 19.6 to $21.4 \text{ g kg}^{-1} \text{ N}$, except at L3, where lower N concentrations were observed ($13.3\text{-}20.4 \text{ g kg}^{-1} \text{ N}$). In contrast, K concentrations in the AGB differed significantly according to the fertilization management practices adopted. In general, except at L4, the highest K concentrations in the AGB were observed under T2 and T6, with mean concentrations of 34 g kg^{-1} in both treatments, representing an average increase of 55% compared with the other management systems.

3.4 Plant Height and Chlorophyll Index

Plant height varied among the study sites (Fig. 5a). No significant differences among treatments were observed at L2 and L4; however, these sites showed the highest mean plant heights among the evaluated areas, reaching 99.2 and 106 cm, respectively. In contrast, at L1, treatments had a significant effect on plant height. The application of T6 and T5 resulted in an average increase of 11.7 cm compared with T1, T2, and T3, indicating a positive response to the adopted management practices. Similarly, at L3, treatment T5 resulted in greater plant height (92 cm), representing an increase of 8 cm compared with the control treatment. The chlorophyll index showed distinct responses among the

evaluated sites. At L1, no significant differences among treatments were observed, indicating no response of this parameter to the management strategies adopted. In contrast, significant treatment effects were observed at L2 and L4, with the highest chlorophyll index values recorded under T6, which resulted in mean increases of 14.6 and 13.9 units, respectively, compared with the other management practices. At L3, the highest chlorophyll index values were observed under conventional management; however, no statistical difference was observed compared with T6, indicating similar performance between these treatments at this site.

3.5 Grain Yield

Rice GY was significantly influenced by the potassium fertilization sources, with responses varying among the experimental sites (Fig. 6). At L1, treatments T2 and T5 showed statistically similar GY, resulting in average increases of 1.62 Mg ha^{-1} (31.4%) compared with the other treatments. Similarly, at L2 and L3, the application of T5 resulted in the highest GY, reaching 8.6 and 10 Mg ha^{-1} , respectively. At both sites, this represented an average increase of 2.7 Mg ha^{-1} compared with the control treatment. In contrast, at L4, treatment T5 resulted in the lowest GY, with an average reduction of 2.9 Mg ha^{-1} (22.8%) compared with T6. The latter reached 12.7 Mg ha^{-1} , representing the highest GY observed across all treatments and experimental sites.

3.6 Soil K Balance

Potassium inputs via fertilization ranged from 50 to 55 kg ha^{-1} , substantially exceeding K outputs through grain export ($13\text{--}32 \text{ kg ha}^{-1}$), resulting in a positive KB in the system at all sites ($19\text{--}40 \text{ kg ha}^{-1}$). This surplus may have been reflected in the increase in $K_{\text{exch-M}}$, which showed increases across most sites and treatments, particularly at L2 and L3, where the increases were more pronounced. Overall, the results indicate that the positive KB in the system was accompanied by an increase in $K_{\text{exch-M}}$, evidencing K accumulation in the readily plant-available fraction within the 0-0.20 m soil layer.

4 Discussion

Our findings support the use of K-bearing remineralizers as potassium fertilizer sources in rice-growing fields in southern Brazil, with agronomic performance comparable to that of conventional KCl (Fig. 6; Table 3). Overall, increased K accumulation in plant biomass and improvements in GY were observed at certain sites, although responses varied among locations. Compared with conventional K fertilizers, these minerals represent locally available alternative K sources with potential to reduce dependence on highly soluble and predominantly imported fertilizers such as KCl (Manning & Theodoro, 2020; Swoboda et al., 2022). These results are consistent with previous studies demonstrating the potential of remineralizers as alternative K sources, contributing to the gradual release of this nutrient and to crop agronomic performance (Harley & Gilkes, 2000; Kelland et al., 2020).

4.1 Soil K Fractions

The K extracted by the K_{exch}-M and K_{exch}-AA methods represented only a small fraction of K_{total}, ranging approximately from 0.2-1.0% and 0.05–0.2%, respectively. This pattern confirms that most soil K occurs in structural or non-exchangeable forms, which are poorly accessible in the short term, and that changes in K availability are mainly associated with the more labile fractions (Lalitha and Dhakshinamoorthy, 2014). Similar values of exchangeable K (~ 0.2% of K_{total}) have been reported in studies conducted in the same region, in soils with similar characteristics but under different management systems (Flores et al., 2021). Thus, chemical extractants reflect only the more dynamic and functional fraction of K in the soil-plant system. In general, the alternative K sources showed K_{exch}-M and K_{exch}-AA levels comparable to those observed with KCl application, indicating that, despite their lower initial solubility, the remineralizers were able to sustain K availability at levels similar to those provided by the conventional fertilizer. In this regard, part of the structural K present in silicate minerals may have contributed to replenishing the exchangeable K pool during irrigated rice cultivation, acting as a secondary source of gradual K release. This behavior is closely related to the mineralogy of these soils, which are often rich in feldspars, micas, and 2:1 clay mineral that act as reservoirs of structural K (Castilhos et al., 2002; Moterle et al., 2019). In irrigated rice systems, flooding induces changes in the soil physicochemical conditions, including changes in redox potential, microbial activity, and soil solution composition (Fageria et al., 2011). The reduction in redox potential, together with increased microbial activity and changes in soil solution composition, may favor the partial destabilization of mineral structures, contributing to the release of K into the soil solution (Ponnamperuma, 1972; Britzke et al., 2012). However, this process is limited in the short term because most K remains associated with structural forms of low reactivity. In this context, the application of remineralizers may act as an additional source of potentially available K, since fine grinding increases the surface area and reactivity of minerals (Swoboda et al., 2022), thereby favoring their gradual dissolution and the release of K into exchangeable and solution forms. Another relevant aspect is the timing of K fertilizer application (Singh et al., 2021). In the present study, except for KCl, the K sources were applied during the winter, prior to the cultivation of Persian clover, followed by rice cultivation. This interval between application and the period of greatest crop K demand may have favored the action of slow-release sources, allowing greater synchronization between K release and plant uptake. Under conditions prone to K leaching, less soluble K-bearing rocks may reduce K losses compared with highly soluble KCl, while providing a slower source of K (Silveira et al., 2025). The analysis of K balances in the system reinforces this interpretation (Table 3). In some cases, the increase in exchangeable soil K was similar to or greater than the apparent KB, indicating that part of the available K did not originate exclusively from the applied fertilizers. This decoupling between K inputs and increases in available K fractions highlights the contribution of internal sources, particularly structural K. Although the remineralizers generally showed behavior similar to KCl in maintaining exchangeable K, their efficiency in releasing K may vary according to their mineralogical composition and the type of K-bearing mineral present in each source (Lalitha and Dhakshinamoorthy, 2014; Kurokawa et al., 2025). This mineralogical variability was confirmed by the XRD analyses, which revealed differences in the K-bearing minerals among the evaluated remineralizers (Fig. 3). Recent evidence indicates that K-bearing minerals differ markedly in their contribution to potentially available K, with K-bearing micas generally representing important reservoirs of potentially available K, although their

contribution depends on mineral type and extraction conditions (Kurokawa et al., 2025). When incorporated into the soil, these mineralogical differences directly affect the rate of K release into the soil solution, particularly under redox conditions that modulate mineral dissolution and ion-exchange processes.

Rocks rich in alkali feldspars, such as phonolite, syenite, and nepheline syenite, tend to release K more rapidly than structurally more stable minerals. In contrast, materials such as mica schist contain K associated with micas, in which K remains more stably held between mineral layers, resulting in a more gradual release of the nutrient (Swoboda et al., 2022). These differences control the kinetics of K release and explain the variability observed among treatments and sites, reinforcing the importance of soil-specific conditions (Awoniyi et al., 2025; Kurokawa et al., 2025). Overall, the results indicate that, despite their lower solubility compared with conventional fertilizer, the remineralizers were able to maintain exchangeable K levels similar to those observed under KCl fertilization. This behavior reinforces the potential of these materials as sustainable alternatives for K management, particularly in systems where soil conditions favor the mobilization of mineral reserves. The absence of significant differences among treatments within the same site suggests that the immediate availability of K is strongly buffered by the soil mineral reservoir, reducing the system's dependence on fertilizer inputs alone.

4.2 Mineral Nutrition Using Alternative K Sources and the Physiological Response of Irrigated Rice

Based on the patterns observed in soil K dynamics (Section 4.1), in which the remineralizers were able to maintain labile K fractions at levels similar to those observed with KCl, K availability in the system appears to be a key factor regulating plant K uptake and physiological responses. In this context, the assessment of nutrient concentrations in the AGB, combined with growth parameters, provides insights into how different K sources influence the nutritional status and physiological performance of irrigated rice plants. Nitrogen concentrations in the AGB did not differ significantly among treatments at any of the four evaluated sites (Fig. 4a), indicating that K fertilization had no direct effect on plant N nutrition. This behavior suggests that N availability was predominantly determined by local soil conditions and management practices. Nevertheless, K nutrition may indirectly influence N use by plants, particularly through its role in processes regulating nutrient assimilation and transport (Cao et al., 2025). In contrast, K concentrations in the AGB were significantly affected by the treatments (Fig. 4b), demonstrating the influence of K sources on plant nutrition. The highest values were observed in the KCl (T2) and mica schist (T6) treatments. While the response to KCl was expected due to its high solubility, the performance of mica schist indicates that this source was able to efficiently supply K throughout the crop cycle. This result is consistent with the patterns observed for exchangeable K in the soil, reinforcing the direct relationship between K availability in labile soil fractions and plant K uptake. Potassium plays central roles in plant physiological regulation, including osmotic control, stomatal function, enzyme activation, and photoassimilate transport, and is therefore essential for maintaining metabolic activity and plant growth (Johnson et al., 2022; Yang et al., 2024). Thus, variation in K concentrations in the AGB provides a mechanistic link between soil K dynamics and plant physiological responses (Sardans and

Peñuelas, 2021). As a consequence of these physiological functions, plant growth responses reflected variations in K availability and uptake among treatments. Plant height varied among sites and treatments (Fig. 5a), with higher values associated with the use of remineralizers at L1 (T5 and T6) and L3 (T5). These results suggest that, under these conditions, K supply from these sources was sufficient to sustain vegetative growth. This behavior is consistent with the physiological functions of K described above and may be related to the maintenance of a more stable nutrient supply throughout the crop cycle, thereby promoting growth under conditions of potentially limited immediate K availability. A similar pattern was observed in plant physiological responses. The chlorophyll index varied among sites and treatments (Fig. 5b). The absence of significant differences at L1 indicates adequate nutritional conditions regardless of the K source applied. In contrast, the higher values observed under T6 at L2 and L4 suggest a better physiological status of plants under these conditions. Consistent with the role of K discussed above, this response may be associated with improved physiological conditions supporting photosynthetic activity. Overall, the results indicate that maintaining soil K availability, even when supplied by less soluble sources, was sufficient to sustain plant nutritional status and promote positive responses in physiological and growth attributes. These responses provide the physiological basis for the variations in GY observed among treatments, which are discussed in the following section.

4.3 Rice Grain Yield

4.3.1 Effect of Environment on Grain Yield

GY reflected differences in K availability and utilization throughout the system. The hypothesis that silicate minerals can replace conventional KCl fertilization while maintaining crop productivity and nutritional performance was partially supported, as the responses across environments indicate that the efficiency of K sources is strongly influenced by soil and climatic factors. Overall, minerals such as nepheline syenite and mica schist showed potential to partially replace soluble K sources, although their performance was dependent on the kinetics of exchangeable K release and their interaction with soil properties (Manning et al., 2017; Nogueira et al., 2021). The contrasting responses among sites indicate that the efficiency of these materials is not an intrinsic property of rock dust use but is also strongly dependent on the context of application, particularly in lowland systems, where redox conditions and ionic dynamics regulate K availability (Castilhos et al., 2002). Whereas KCl undergoes rapid dissolution and is more susceptible to K losses through leaching, minerals such as mica schist and nepheline syenite act as slow-release sources, promoting continuous replenishment of K in the soil solution and greater stability in nutrient availability (Swoboda et al., 2022). In tropical and subtropical soils, which are often highly weathered and have a low capacity to retain cations, this characteristic becomes particularly relevant, especially in irrigated systems where water dynamics can intensify nutrient transport through the soil profile (Castilhos et al., 2002). Therefore, the agronomic performance of these silicate minerals is associated with their controlled dissolution process, which may promote greater synchronization between K supply and crop demand throughout the growing cycle. This synchronization may contribute to increased nutrient use efficiency and reduce potential K losses in intensive agricultural systems.

4.3.2. Potential Replacement of KCl with Silicate Rock Dust

From an agronomic perspective, silicate sources, particularly T5 and T6, show potential for use as alternative K sources. Their use may reduce dependence on highly soluble fertilizers and increase nutrient use efficiency, thereby contributing to more sustainable nutrient management strategies. In addition, the use of silicate rock dust may promote the valorization of mining residues and contribute to reducing dependence on imported K fertilizers.

However, the strong dependence on soil and climatic conditions indicates that their use should be tailored to the specific environment to maximize their effectiveness. In addition, the experimental period may not have been sufficient to fully capture the long-term effects associated with the dissolution of silicate minerals and their cumulative contribution to soil K fertility. Given that mineral weathering is a gradual process, the benefits of these materials may become more evident over successive cropping cycles (Ribeiro et al., 2025).

Future studies should include long-term evaluations across different soil classes and climatic conditions, focusing on K release kinetics, soil-mineral interactions, and the stability of agronomic responses over time. Additionally, the integration of silicate minerals with conventional fertilizer sources and different management strategies should be investigated to optimize their use and improve agronomic performance in agricultural systems.

5. Conclusions

The use of phonolite, nepheline syenite, and mica schist as alternative K sources to KCl maintained exchangeable K concentrations in the soil at levels similar to or higher than those observed under conventional K fertilization.

The maintenance of irrigated rice GY, particularly under the application of nepheline syenite and mica schist, indicates agronomic efficiency comparable to that of KCl among the alternative K sources. In addition, the rock dusts promoted greater K accumulation in plant biomass, increased the chlorophyll index, and resulted in a more favorable exchangeable KB in the soil compared with the soluble fertilizer.

Overall, the results demonstrate that K sources derived from rock dust constitute viable alternatives to conventional K fertilizers in subtropical rice-growing systems. These findings contribute to the development of more resilient and sustainable agroecosystems for irrigated rice production.

Declarations

Author Contribution

F.S.C. and V.L.V. conceived and designed the study. V.L.V., R.B.R., E.H.P., T.V.C., A.S.O., R.O.S., P.A.S., and F.S.C. conducted the field experiments and collected the data. V.L.V., R.B.R., E.H.P., T.V.C., and F.S.C. performed the data analysis. F.S.C. and V.L.V. interpreted the results. F.S.C. wrote the original draft of the

manuscript. W.B.S. and E.C.B. contributed to the interpretation of the results and critically revised the manuscript. All authors reviewed and approved the final version of the manuscript.

Acknowledgement

We gratefully acknowledge the financial support from Brazil's National Council for Scientific and Technological Development (CNPq, Grant No. 407900/2022-5) and the Brazilian Funding Authority for Studies and Projects (FINEP, Project Nos. 0932/25 and 1292/25).

Data Availability

The data generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

References

1. ANDA - Agência Nacional para Distribuição de Adubos. (2019). Principais indicadores. Recuperado em 20 de março de 2025, de http://anda.org.br/wp-content/uploads/2019/06/Principais_Indicadores_2019.pdf
2. Awoniyi, A. S., Adeyemo, A. J., Agbenin, J. O., et al. (2025). Potassium release from K-bearing minerals treated with organic acids under laboratory conditions. *Discover Soil*, 2, 69. <https://doi.org/10.1007/s44378-025-00096-7>.
3. Basak, B. B. (2019). Waste mica as alternative source of plant-available potassium: Evaluation of agronomic potential through chemical and biological methods. *Natural Resources Research*, 28(3), 953–970. <https://doi.org/10.1007/s11053-018-9430-3>
4. Beerling, D. J., Kantzas, E. P., Lomas, M. R., et al. (2020). Potential for large-scale CO₂ removal via enhanced rock weathering with croplands. *Nature*, 583, 242–248. <https://doi.org/10.1038/s41586-020-2448-9>
5. Boeni, M., Anghinoni, I., Genro Junior, S. A., & Osório Filho, B. D. (2010). Evolução da fertilidade dos solos cultivados com arroz irrigado no Rio Grande do Sul. Porto Alegre.
6. Brasil, Ministério da Agricultura, Pecuária e Abastecimento. (2016). Instrução Normativa nº 5, de 10 de março de 2016. *Diário Oficial da República Federativa do Brasil*. Recuperado em 13 de março de 2025, de https://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/21393137/do1-2016-03-14-instrucao-normativa-n-5-de-10-de-marco-de-2016-21393106
7. Brindley, G. W., & Brown, G. (Eds.). (1980). *Crystal structures of clay minerals and their X-ray identification*. London: Mineralogical Society. <https://doi.org/10.1180/mono-5>.

8. Britzke, D., Silva, L. S., Moterle, D. F., & Bortoluzzi, E. C. (2012). A study of potassium dynamics and mineralogy in soils from subtropical Brazilian lowlands. *Journal of Soils and Sediments*, 12(2), 185–197. <https://doi.org/10.1007/s11368-011-0431-7>.
9. Castilhos, R. M., Meurer, E. J., Kämpf, N., & Pinto, L. F. S. (2002). Mineralogia e fontes de potássio em solos no Rio Grande do Sul cultivados com arroz irrigado. *Revista Brasileira de Ciência do Solo*, 26(3), 579–587. <https://doi.org/10.1590/S0100-06832002000300002>
10. Chaudhary, M., Singh, B. R., Krogstad, T., & Heim, M. (2011). Liberação de cobre, zinco e manganês de pó de rocha com materiais orgânicos aplicados ao solo. *Communications in Soil Science and Plant Analysis*, 42(21), 2682–2697. <https://doi.org/10.1080/00103624.2011.614042>
11. CNA – Confederação da Agricultura e Pecuária do Brasil. (2024). Novos projetos de fomento de NPK no Brasil miram reduzir a dependência internacional. Recuperado em 20 de março de 2025, de <https://www.cnabrazil.org.br/noticias/novos-projetos-de-fomento-de-npk-no-brasil-miram-reduzir-a-dependencia-internacional>
12. Counce, P. A., Keisling, T. C., & Mitchell, A. J. (2000). A uniform, objective, and adaptive system for expressing rice development. *Crop Science*, 40(2), 436–443. <https://doi.org/10.2135/cropsci2000.402436x>.
13. CQFS-RS/SC - Commission of Chemistry and Soil Fertility, 2016. Manual de calagem e adubação para os estados do Rio Grande do Sul e Santa Catarina. Rio Grande do Sul: Comissão de Química e Fertilidade do Solo.
14. Daniell, A., & Van Tonder, D. M. (2023). Opportunity for increasing the soil quality of non-arable and depleted soils in South Africa: A review. *Journal of Soil Science and Plant Nutrition*, 23(2), 2476–2487. <https://doi.org/10.1007/s42729-023-01205-7>.
15. Fageria, N. K., Carvalho, G. D., Santos, A. B., Ferreira, E. P. B., & Knupp, A. M. (2011). Chemistry of lowland rice soils and nutrient availability. *Communications in Soil Science and Plant Analysis*, 42(16), 1913–1933. <https://doi.org/10.1080/00103624.2011.591467>
16. Farias, P. I. V., Freire, E., Cunha, A. L. C., Grumbach, R. J. S., & Antunes, A. M. S. (2020). The fertilizer industry in Brazil and the assurance of inputs for biofuels production: Prospective scenarios after COVID-19. *Sustainability*, 12, 8889. <https://doi.org/10.3390/su12218889>
17. Flores, J. P. M., Alves, L. A., Denardin, L. G. de O., Martins, A. P., Bortoluzzi, E. C., Inda, A. V., Carvalho, P. C. de F., & Tiecher, T. (2021). Soil K forms and K budget in integrated crop-livestock systems in subtropical paddy fields. *Soil and Tillage Research*, 213, 105070. <https://doi.org/10.1016/j.still.2021.105070>.
18. Geilfus, C.-M. (2019). Chloride in soil: From nutrient to soil pollutant. *Environmental and Experimental Botany*, 157, 299–309. <https://doi.org/10.1016/j.envexpbot.2018.10.035>
19. Harley, A., & Gilkes, R. (2000). Factors influencing the release of plant nutrient elements from silicate rock powders: A geochemical overview. *Nutrient Cycling in Agroecosystems*, 56, 11–36. <https://doi.org/10.1023/A:1009859309453>

20. Johnson, R., Vishwakarma, K., Hossen, M. S., Kumar, V., Shackira, A. M., Puthur, J. T., Abdi, G., Sarraf, M., & Hasanuzzaman, M. (2022). Potassium in plants: Growth regulation, signaling, and environmental stress tolerance. *Plant Physiology and Biochemistry*, 172, 56–69. <https://doi.org/10.1016/j.plaphy.2022.01.001>
21. Kelland, M. E., Wade, P. W., Lewis, A. L., Taylor, L. L., Sarkar, B., Andrews, M. G., Lomas, M. R., Cotton, T. E. A., Kemp, S. J., James, R. H., Pearce, C. R., Hartley, S. E., Hodson, M. E., Leake, J. R., Banwart, S. A., & Beerling, D. J. (2020). Increased yield and CO₂ sequestration potential with the C₄ cereal *Sorghum bicolor* cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology*, 26(6), 3658–3676. <https://doi.org/10.1111/gcb.15089>
22. Kurokawa, K., Nakao, A., Suzuki, A., Wakabayashi, S., Fujimura, S., Eguchi, T., Shinano, T., & Yanai, J. (2025). Soil K-bearing minerals respond differently to various potassium extraction methods targeting phytoavailability. *Soil Science Society of America Journal*, 89(6), 1–12. <https://doi.org/10.1002/saj2.70160>
23. Lalitha, M., & Dhakshinamoorthy, M. (2014). Forms of soil potassium: A review. *Agricultural Reviews*, 35(1), 64–73. <https://doi.org/10.5958/j.0976-0741.35.1.008>
24. Manning, D. A. C. (2010). Mineral sources of potassium for plant nutrition: A review. *Agronomy for Sustainable Development*, 30, 281–294. <https://doi.org/10.1051/agro/2009023>
25. Manning, D. A. C., & Theodoro, S. H. (2020). Enabling food security through use of local rocks and minerals. *The Extractive Industries and Society*, 7(2), 480–487. <https://doi.org/10.1016/j.exis.2018.11.002>
26. Manning, D. A. C., Baptista, J., Limon, M. S., & Brandt, K. (2017). Testing the ability of plants to access potassium from framework silicate minerals. *Science of the Total Environment*, 574, 476–481. <https://doi.org/10.1016/j.scitotenv.2016.09.086>
27. Marques Neto, G. C., Vahl, L. C., Sousa, R. O. de, Peres, M. M., Vale, M. L. C. do, & Carlos, F. S. (2023). Understanding the dynamics of attributes of medium and short cycle rice cultivars under nitrogen effect. *Ciência Rural*, 53(1), 1–16. <https://doi.org/10.1590/0103-8478cr20210584>.
28. Mindat.org. (2024). Mindat.org: The world's largest open database of minerals, rocks, and localities. Hudson Institute of Mineralogy. <https://www.mindat.org/>
29. Moterle, D. F., Bortoluzzi, E. C., Kaminski, J., Rheinheimer, D. S., & Caner, L. (2019). Does Ferralsol clay mineralogy maintain potassium long-term supply to plants? *Revista Brasileira de Ciência do Solo*, 43, e0180166. <https://doi.org/10.1590/18069657rbcs20180166>
30. Nogueira, T. A. R., Miranda, B. G., Jalal, A., Lessa, L. G. F., Teixeira Filho, M. C. M., Marcante, N. C., Abreu-Junior, C. H., Jani, A. D., Capra, G. F., Moreira, A., et al. (2021). Nepheline syenite and phonolite as alternative potassium sources for corn. *Agronomy*, 11(7), 1385. <https://doi.org/10.3390/agronomy11071385>
31. Ponnampereuma, F. N. (1972). The chemistry of submerged soils. *Advances in Agronomy*, 24, 29–96.
32. Ramos, C. G., Hower, J. C., Blanco, E., Oliveira, M. L. S., & Theodoro, S. H. (2022). Possibilities of using silicate rock powder: An overview. *Geoscience Frontiers*, 13(1), 101185.

<https://doi.org/10.1016/j.gsf.2021.101185>

33. Reis, B. R., Vasconcelos, A. L. S., Silva, A. M. M., Andreote, F. D., & Azevedo, A. C. (2024). Changes in soil bacterial community structure in a short-term trial with different silicate rock powders. *Chemical and Biological Technologies in Agriculture*, 11(1), 1–16. <https://doi.org/10.1186/s40538-024-00586-w>
34. Ribas, G. G., Heinemann, A. B., Stone, L. F., de Castro, A. P., Streck, N. A., dos Santos, A. B., da Silva, M. R., Steinmetz, S., Soares, C. F., & Zanon, A. J. (2025). Rice-based cropping systems in Brazil: Irrigated and rainfed. *Crop and Environment*, 4, 256–262. <https://doi.org/10.1016/j.crope.2025.07.002>.
35. Ribas, G. G., Zanon, A. J., Streck, N. A., Pilecco, I. B., Souza, P. M., Heinemann, A. B., & Grassini, P. (2021). Assessing yield and economic impact of introducing soybean to the lowland rice system in southern Brazil. *Agricultural Systems*, 188, 103036. <https://doi.org/10.1016/j.agsy.2020.103036>.
36. Ribeiro, M. C., Martins, A. R., Alves, R. S., Lessa, L. G. F., Pereira, H. S., Galindo, F. S., Teixeira Filho, M. C. M., Abreu-Junior, C. H., Jani, A. D., & Capra, G. F. (2025). Basalt rock dust as a soil remineralizer in upland rice grown in tropical soils: Residual effects on soil fertility, Si availability, and leaf anatomy. *Journal of Cleaner Production*, 520, 146063. <https://doi.org/10.1016/j.jclepro.2025.146063>
37. Sardans, J., & Peñuelas, J. (2021). Potassium control of plant functions: Ecological and agricultural implications. *Plants*, 10(2), 419. <https://doi.org/10.3390/plants10020419>
38. Silveira, C. P., Soares, J. R., Montes, R. M., Saviato, J., & Otto, R. (2025). Blending potassium rocks with KCl fertilizer to enhance crop biomass and reduce K leaching in sandy soil. *Soil Systems*, 9(3), 83. <https://doi.org/10.3390/soilsystems9030083>
39. Singh, V. K., Dwivedi, B. S., Rathore, S. S., Mishra, R. P., Satyanarayana, T., & Majumdar, K. (2021). Synchronizing potassium application with plant demand. In T. S. Murrell, R. L. Mikkelsen, G. Sulewski, R. Norton, & M. L. Thompson (Eds.), *Improving potassium recommendations for agricultural crops* (pp. 259–278). Springer. https://doi.org/10.1007/978-3-030-59197-7_13
40. SOSBAI – South Brazilian Society of Irrigated Rice. (2025). *Irrigated rice: Technical recommendations from research for Southern Brazil*. Santa Maria: UFSM; Porto Alegre: SOSBAI.
41. Sousa, R. O., Carlos, F. S., Silva, L. S., Scivittaro, W. B., Ribeiro, P. L., & Lima, C. L. R. (2021). No-tillage for flooded rice in Brazilian subtropical paddy fields: History, challenges, advances and perspectives. *Revista Brasileira de Ciência do Solo*, 45, e20210102. <https://doi.org/10.36783/18069657rbcs20210102>
42. Strefler, J., Amann, T., Bauer, N., Kriegler, E., & Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, 13, 034010. <https://doi.org/10.1088/1748-9326/aaa9c4>
43. Swoboda, P., Döring, T. F., & Hamer, M. (2022). Remineralizing soils? The agricultural usage of silicate rock powders: A review. *Science of the Total Environment*, 807, 150976. <https://doi.org/10.1016/j.scitotenv.2021.150976>

44. Tedesco, M. J., Gianello, C., Bissani, C. A., Bohnen, H., & Volkweiss, S. J. (1995). Análises de solo, plantas e outros materiais. Porto Alegre: Universidade Federal do Rio Grande do Sul.
45. USDA, 2014. Keys to Soil Taxonomy, 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service.
46. Wang, F., Zhu, F., Liu, D., et al. (2024). A aplicação de pó de wollastonita aumenta a produtividade do arroz e o sequestro de CO₂ em um arrozal no nordeste da China. *Plant and Soil*, 502, 589–603. <https://doi.org/10.1007/s11104-024-06570-5>
47. WebMineral. (2024). WebMineral: Mineralogy database. <https://webmineral.com/>.
48. Wrege, M. S., et al. (2011). Climate atlas: Rio Grande do Sul. Porto Alegre: CEMETRS, FEPAGRO. <http://www.r3pb.com.br/AtlasCemetRS>.
49. Yang, C., Lu, J., Xiong, Z., Wang, B., Ren, T., Cong, R., Lu, Z., & Li, X. (2024). Potassium deficiency enhances imbalances in rice water relations under water deficit by decreasing leaf hydraulic conductance. *Physiologia Plantarum*, 176(3), e14360. <https://doi.org/10.1111/ppl.14360>.

Tables

Table 1. Chemical characteristics of the study sites before the beginning of the experiments, 2023/24 growing season.

Location	Layer	Clay	OM	pH	P	K	Ca	Al	Mg	CEC pH 7.0	V
	(m)	%.....		(1:1)	mg dm ⁻³		cmol _c dm ⁻³				(%)
L1	0-0.2	23	1.66	6.1	13.3	44.0	4.3	0.0	2.1	8.3	80
L2		23	1.10	6.5	30.5	91.0	5.3	0.0	2.8	10.1	85
L3		20	0.97	6.8	30.5	74.0	4.3	0.0	2.4	8.3	85
L4		19	1.66	6.2	121.2	123.0	5.5	0.0	2.5	10.2	83

Organic matter (OM), phosphorus (P), potassium (K), calcium (Ca), aluminum (Al), magnesium (Mg), cation exchange capacity at pH 7.0 (CEC), and base saturation (V).

Table 2. Description of treatments with different agrominerals used in an irrigated rice experiment.

Treatments	Total de K content (%)	Application rates of the sources (kg ha ⁻¹)			
		Palma ³	AUD ³	Capão Grande ⁴	Rio Grande ⁴
T1 - No potassium fertilization	-	-	-	-	-
T2 - Potassium chloride ¹	49.8	221	221	221	221
T3 - Phonolite ²	8.8	3,750	3,750	3,750	3,750
T4 - Syenite ²	8.1	4,075	4,075	4,075	4,075
T5 - Nepheline syenite ²	8.3	3,976	3,976	3,976	3,976
T6 - Mica schist ²	13.0	2,539	2,539	2,539	2,539

¹Readily available potassium (100% water-soluble)

²Slow-release potassium (<1% water-soluble)

Table 3. Cumulative grain yield, K inputs and outputs, and K balance in the 0-20 cm soil layer in rice production systems under different potassium fertilizer sources during the 2023/2024 growing season.

Variable	T1	T2	T3	T4	T5	T6
Location 1: Capão do Leão						
Rice grain yield (Mg ha ⁻¹)	5.4	7.2	5.8	5.6	7.0	5.1
K exported by grains (kg ha ⁻¹)	14	18	15	14	18	13
Total K input via fertilizer (kg ha ⁻¹)	-	55	54	53	53	53
K balance in the system (kg ha ⁻¹)	-	37	40	39	35	40
Initial Mehlich-1 K, 0-20 cm (mg kg ⁻¹)	44	44	44	44	44	44
Final Mehlich-1 K, 0-20 cm (mg kg ⁻¹)	71	73	73	75	72	71
Soil exchangeable K (exch-M) balance (mg kg ⁻¹)	27	29	29	31	28	27
Location 2: Rio Grande						
Rice grain yield (Mg ha ⁻¹)	6.5	7.5	8.1	8.0	8.6	7.3
K exported by grains (kg ha ⁻¹)	16	19	20	20	21	18
Total K input via fertilizer (kg ha ⁻¹)	-	55	54	53	53	53
K balance in the system (kg ha ⁻¹)	-	36	34	33	31	34
Initial Mehlich-1 K, 0-20 cm (mg kg ⁻¹)	91	91	91	91	91	91
Final Mehlich-1 K, 0-20 cm (mg kg ⁻¹)	109	118	162	162	113	171
Soil exchangeable K (exch-M) balance (mg kg ⁻¹)	18	27	71	71	22	80
Location 3: AUD						
Rice grain yield (Mg ha ⁻¹)	6.8	8.0	7.1	7.5	10.1	8.9
K exported by grains (kg ha ⁻¹)	17	20	18	19	25	22
Total K input via fertilizer (kg ha ⁻¹)	-	50	50	50	50	50
K balance in the system (kg ha ⁻¹)	-	30	33	32	25	28
Initial Mehlich-1 K, 0-20 cm (mg kg ⁻¹)	74	74	74	74	74	74
Final Mehlich-1 K, 0-20 cm (mg kg ⁻¹)	101	107	120	117	117	126
Soil exchangeable K (exch-M) balance (mg kg ⁻¹)	27	33	46	43	43	52
Location 4: Capão Grande						

Rice grain yield (Mg ha^{-1})	11.1	12.1	10.0	11.0	9.9	12.7
K exported by grains (kg ha^{-1})	28	30	25	28	25	32
Total K input via fertilizer (kg ha^{-1})	-	50	50	50	50	50
K balance in the system (kg ha^{-1})	-	20	25	23	26	19
Initial Mehlich-1 K, 0-20 cm (mg kg^{-1})	123	123	123	123	123	123
Final Mehlich-1 K, 0-20 cm (mg kg^{-1})	73	73	128	147	115	130
Soil exchangeable K (exch-M) balance (mg kg^{-1})	-50	-50	5	24	-8	7

Treatments: T1 - without potassium fertilization; T2 - potassium chloride; T3 - phonolite; T4 - syenite; T5 - nepheline syenite; T6 - mica schist.

Figures

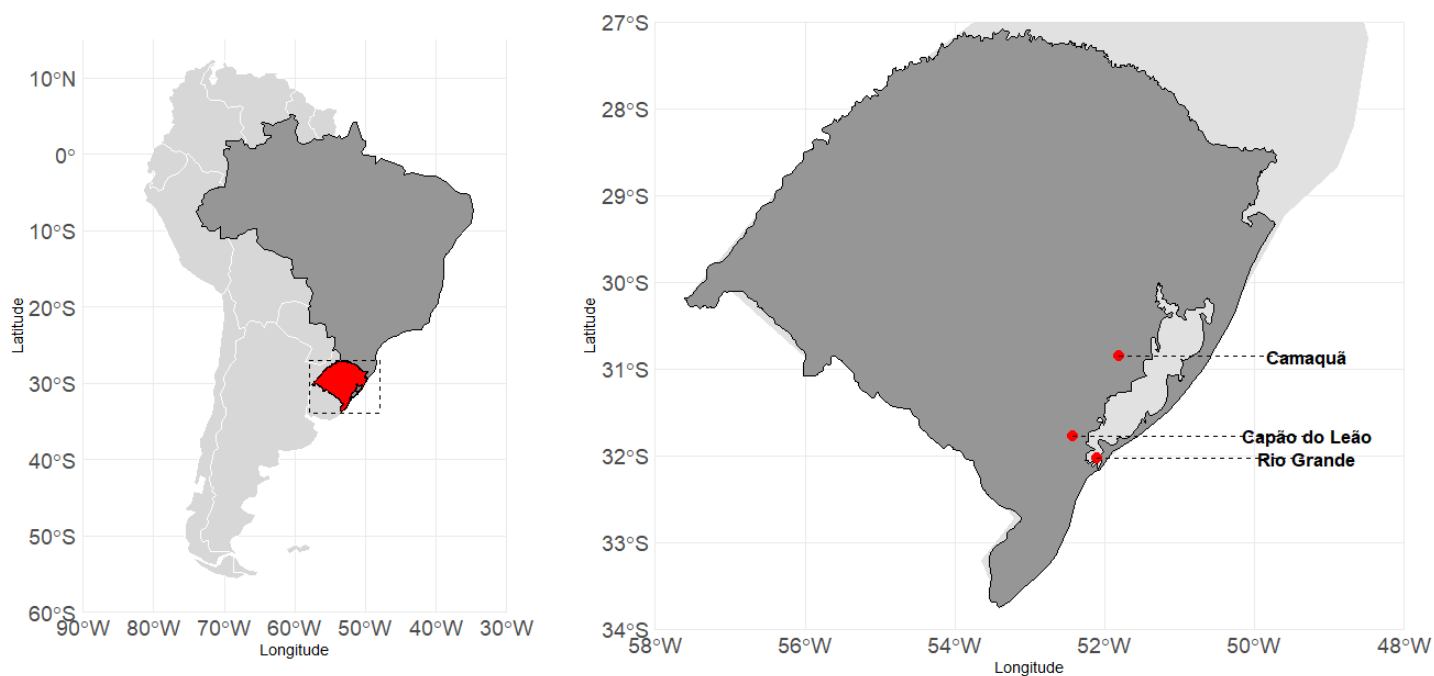


Figure 1

Location of experiments with silicate minerals as potassium sources in irrigated rice in southern Brazil.

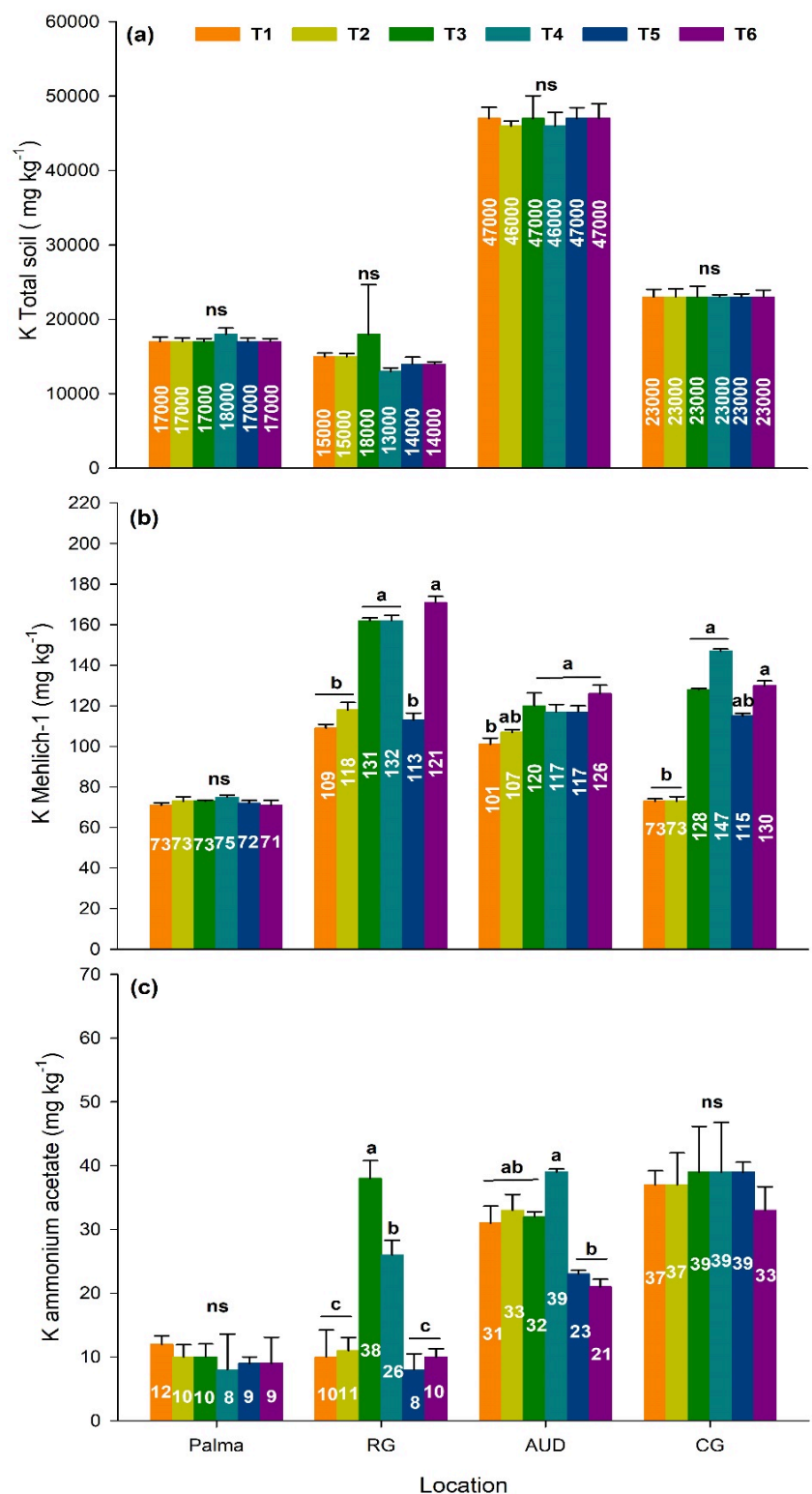


Figure 2

Total K content (a), Mehlich-1-extractable K (b), and ammonium acetate-extractable K (c) in the soil under irrigated rice cultivation with different potassium fertilizer sources in the 2023/2024 growing season. Treatments: T1 - no potassium fertilization; T2 - potassium chloride; T3 - phonolite; T4 - syenite; T5 - nepheline syenite; T6 - mica schist. Locations: L1: Capão do Leão/RS; L2: Rio Grande/RS; L3 and L4:

Camaquã/RS. Different letters within the same location indicate significant differences according to Tukey's test ($p < 0.05$). ns (not significant).

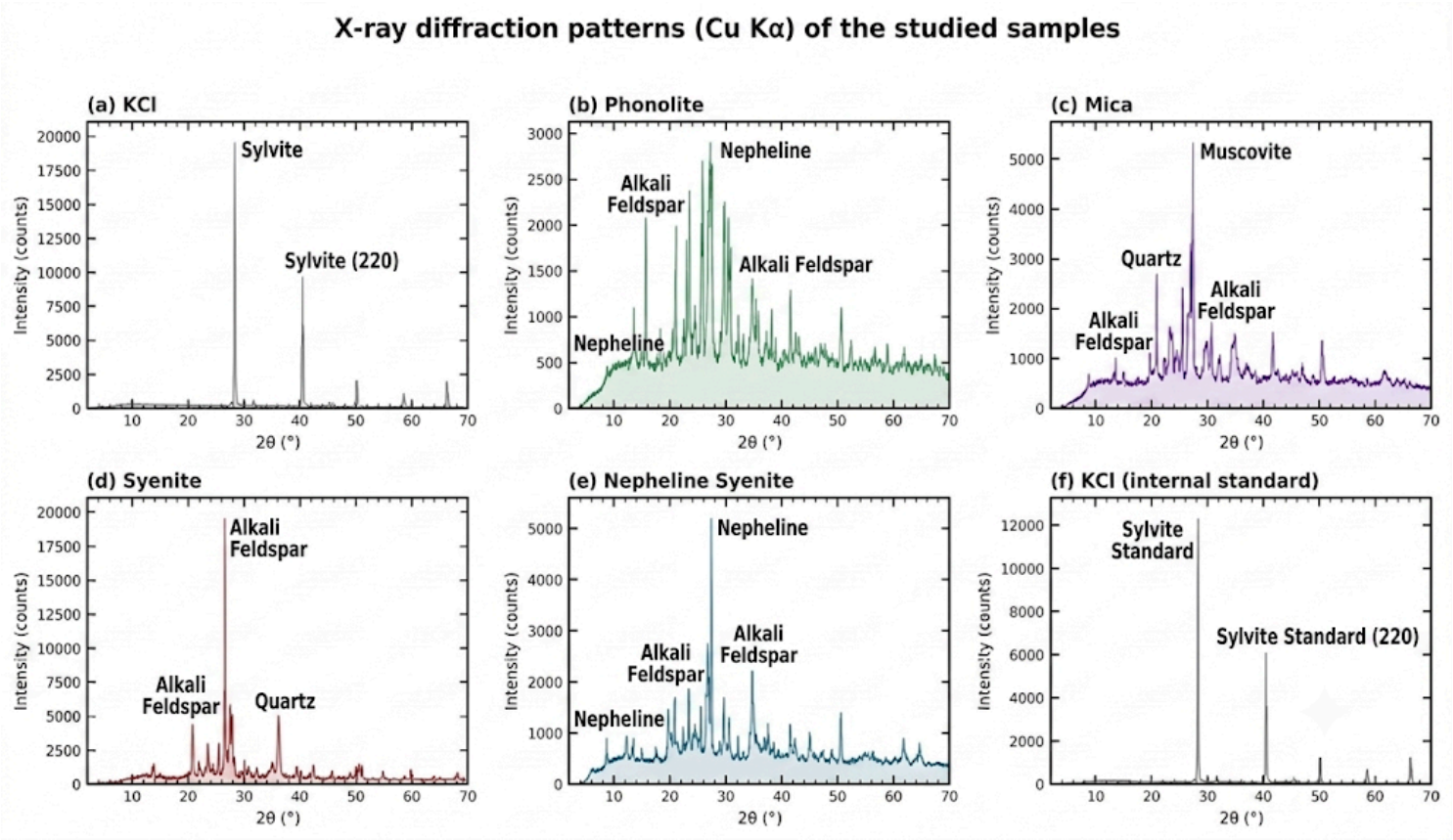


Figure 3

Mineralogical composition of the samples determined by X-ray diffraction (XRD) for phonolite (a), mica (b), syenite (c), and nepheline syenite (d), used as alternative potassium fertilizer sources in irrigated rice production fields during the 2023/2024 growing season.

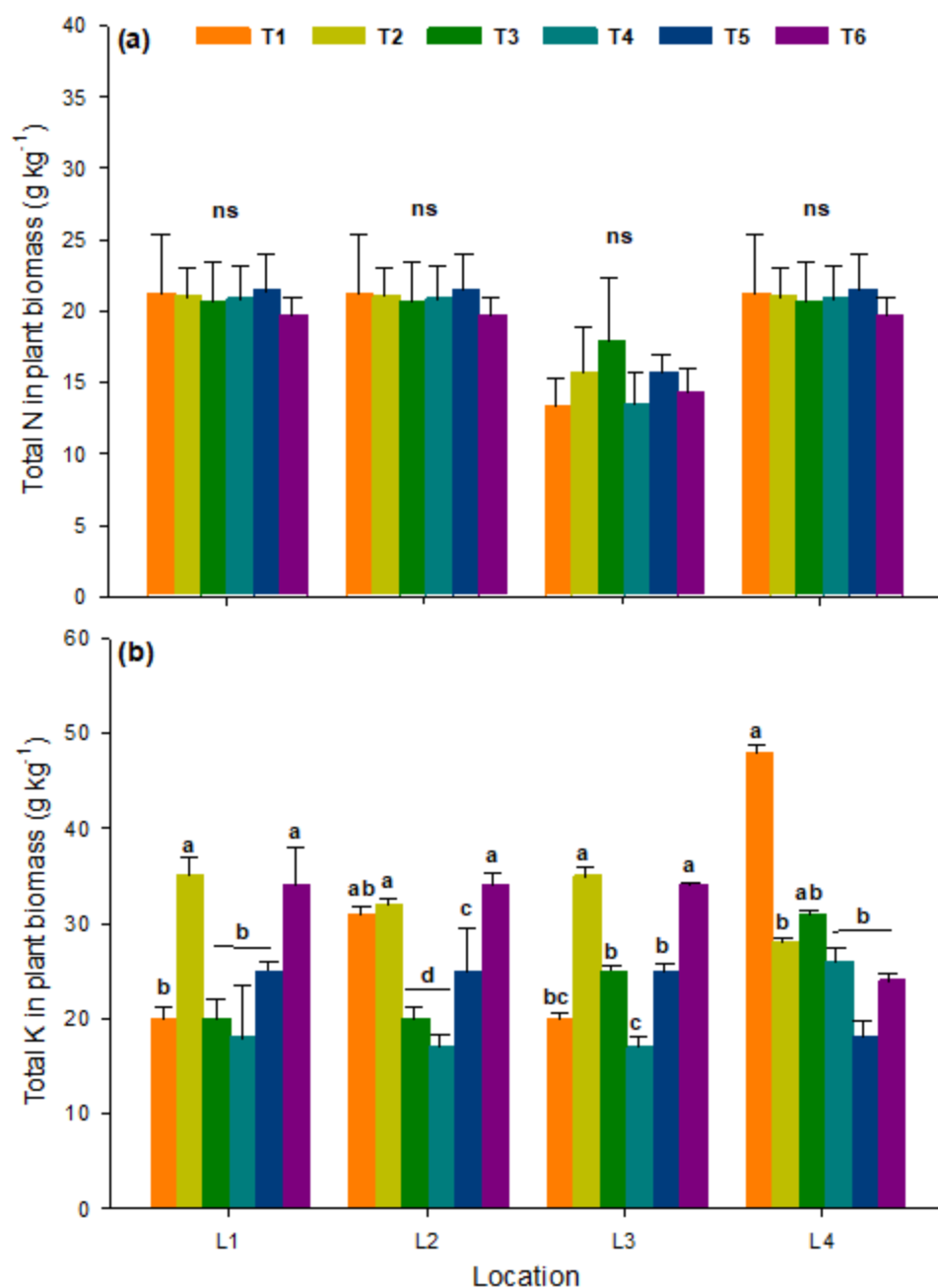


Figure 4

N (a) and K (b) contents in the biomass of irrigated rice plants grown under different potassium fertilizer sources in the 2023/2024 growing season. Treatments: T1 - no potassium fertilization; T2 - potassium chloride; T3 - phonolite; T4 - syenite; T5 - nepheline syenite; T6 - mica schist. Locations: L1: Capão do Leão/RS; L2: Rio Grande/RS; L3 and L4: Camaquã/RS. Different letters within the same location indicate significant differences according to Tukey's test ($p < 0.05$). ns (not significant).

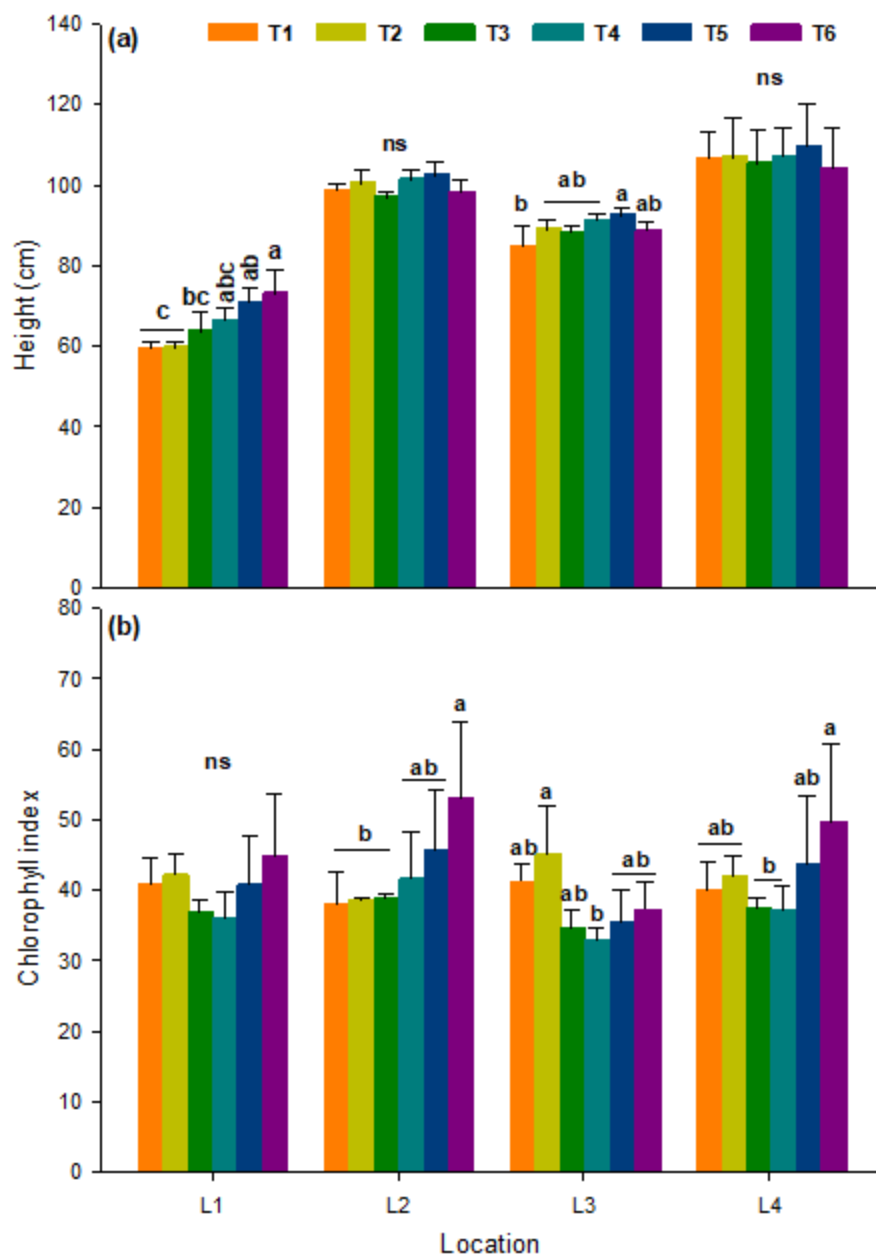


Figure 5

Plant height (a) and chlorophyll index (b) in irrigated rice plants grown under different potassium fertilizer sources in the 2023/2024 growing season. Treatments: T1 - no potassium fertilization; T2 - potassium chloride; T3 - phonolite; T4 - syenite; T5 - nepheline syenite; T6 - mica schist. Locations: L1: Capão do Leão/RS; L2: Rio Grande/RS; L3 and L4: Camaquã/RS. Different letters within the same location indicate significant differences according to Tukey's test ($p < 0.05$). ns (not significant).

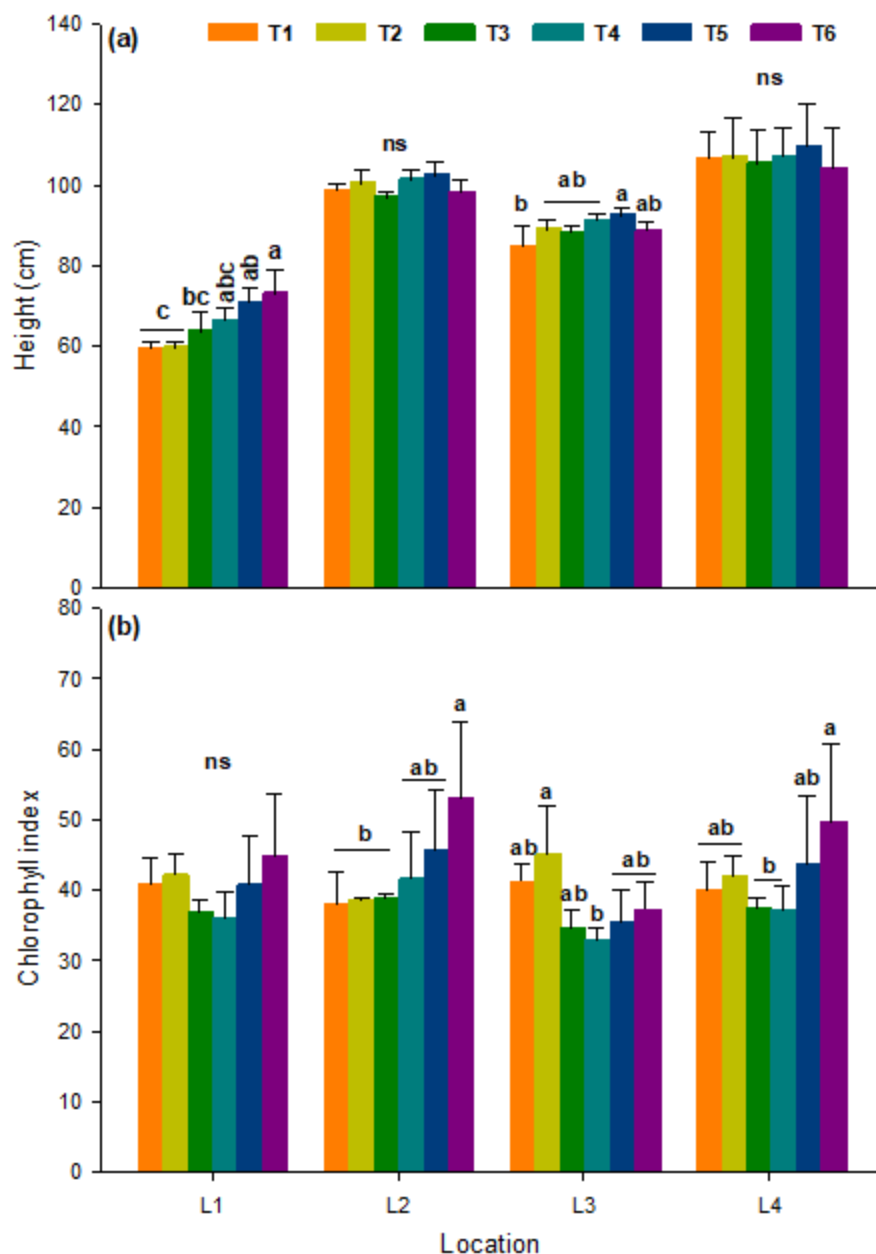


Figure 5

Plant height (a) and chlorophyll index (b) in irrigated rice plants grown under different potassium fertilizer sources in the 2023/2024 growing season. Treatments: T1 - no potassium fertilization; T2 - potassium chloride; T3 - phonolite; T4 - syenite; T5 - nepheline syenite; T6 - mica schist. Locations: L1: Capão do Leão/RS; L2: Rio Grande/RS; L3 and L4: Camaquã/RS. Different letters within the same location indicate significant differences according to Tukey's test ($p < 0.05$). ns (not significant).

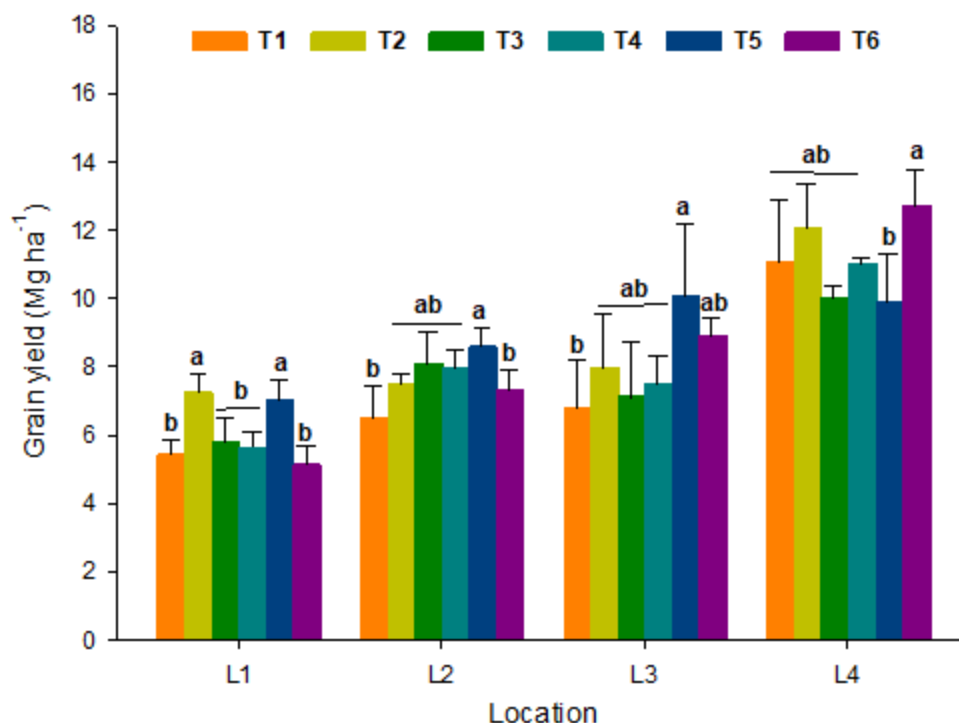


Figure 6

Grain yield of irrigated rice grown under different potassium fertilizer sources in the 2023/2024 growing season. Treatments: T1 - no potassium fertilization; T2 - potassium chloride; T3 - phonolite; T4 - syenite; T5 - nepheline syenite; T6 - mica schist. Locations: L1: Capão do Leão/RS; L2: Rio Grande/RS; L3 and L4: Camaquã/RS. Different letters within the same location indicate significant differences according to Tukey's test ($p < 0.05$). ns (not significant).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [FiguresT.docx](#)