

INTERCROPPING, POTASSIUM SOURCES AND CORN CROP YIELD: AN APPROACH TOWARDS SUSTAINABILITY

CONSÓRCIO DE CULTURAS, FONTES DE POTÁSSIO E PRODUTIVIDADE DO MILHO: UMA ABORDAGEM PARA A SUSTENTABILIDADE

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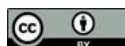
The authors declare that there is no conflict of interest

Abstract

Potassium (K) is an essential macronutrient for plant productivity, but the price and availability of potassium chloride (KCl), the most used K source in Brazil, have been impacted by import

Resumo

O potássio (K) é um macronutriente essencial para a produtividade das plantas, mas o preço e a disponibilidade do cloreto de potássio (KCl), a fonte de K mais usada no Brasil, foram



difficulties. Additionally, Brazilian agriculture has shifted towards integrated systems with multiple crops. Therefore, this study evaluated potassium silicate (K6), a national K source, and its effects on corn (*Zea mays*) grown in single or intercropped systems. The hybrid corn cultivar Santa Helena 7990 PRO 2 was grown in three cultivation systems (single corn, intercropped with *Urochloa ruziziensis*, or intercropped with *Crotalaria spectabilis*) and three K treatments (no K, KCl, or K6). Results showed that intercropping with *Urochloa* reduced plant height, ear number, and grain mass, while *crotalaria* with K6 increased productivity. Although *Urochloa* suppressed weeds better, *crotalaria* with K6 proved to be the most beneficial for corn yield. Therefore, K6 has proven to be a viable alternative to KCl.

Keywords: *Crotalaria Spectabilis*. *Urochloa Ruziziensis*. *Zea Mays*. Rock powder.

*impactados por dificuldades de importação. Além disso, a agricultura brasileira tem adotado sistemas integrados com múltiplas culturas. Este estudo avaliou o silicato de potássio (K6), uma fonte nacional de K, e seus efeitos no milho (*Zea mays*) cultivado em sistemas de cultivo solteiro ou consorciado. A cultivar híbrida de milho Santa Helena 7990 PRO 2 foi cultivada em três sistemas (milho solteiro, consorciado com *Urochloa ruziziensis* ou com *Crotalaria spectabilis*) e três tratamentos de K (sem K, KCl ou K6). Os resultados mostraram que o consórcio com *Urochloa* reduziu a altura das plantas, o número de espigas e a massa de grãos, enquanto a *crotalária* com K6 aumentou a produtividade. Embora a *Urochloa* tenha suprimido melhor as ervas daninhas, a *crotalária* com K6 foi mais benéfica para o rendimento do milho. Assim, o K6 mostrou-se uma alternativa viável ao KCl.*

Palavras-chave: *Crotalaria Spectabilis*. *Urochloa Ruziziensis*. *Zea Mays*. Pó de Rocha.

1 INTRODUCTION

Potassium (K) is a macronutrient absorbed in large quantities by plants, being the most abundant cation in plant crops (Bang *et al.*, 2020). Although K is not found in any plant structure or chemical molecule, it is involved in a number of physiological processes essential for plant metabolism and development. For example, K is necessary for photosynthetic activity, cell turgor maintenance, regulation of stomatal movements, promotion of water absorption, regulation of nutrient translocation, stimulation of carbohydrate transport and storage, increase of nitrogen absorption, promoting protein synthesis, and participates in starch synthesis in leaves (Bang *et al.*, 2020; Sardans & Peñuelas, 2021).

Therefore, farmers are forced to apply large amounts of K to guarantee the necessary supply to agricultural crops. However, potassium chloride (KCl) is a soluble source of K that has chlorine (Cl) as an accompanying ion and is the most used potassium source by farmers around the world (De Oliveira, 2014; Vieira *et al.*, 2016). In fact, KCl is an interesting source of K with high solubility, which results in rapid release of K to crops, as well as a high concentration of K, facilitating the logistics and distribution

operations of this fertilizer. However, its use in an unbalanced manner can have negative consequences for agricultural systems, such as salinization and the accumulation of Cl in the soil (Carvalho & Kazama, 2011; Paula *et al.*, 2020). In addition, world potash (K_2O) production is concentrated in a few countries, such as Canada, Russia, Belarus, China, and Germany, which are responsible for around 80% of world production (Jena, 2021). This makes several countries with large agricultural production dependent on the import of potash, which is a negative factor for the agricultural stability of these countries (Jena, 2021).

Thus, the importance of investing in the search for local sources of K that can, at least partially, replace imported K is clear. Given this scenario, K-rich silicate rocks have proven to be a suitable source of K for various crops due to their lower cost, Cl absence, presence of other elements, and high silicon content (Ribeiro *et al.*, 2010; Soratto *et al.*, 2021). These rocks can even act as soil conditioners, improving their chemical properties (Gomaa *et al.*, 2021; Soratto *et al.*, 2021). In addition to being an accepted source of K in organic agriculture and potentially less aggressive to the soil microbiota. These characteristics establish potassium silicate as a sustainable and environmentally-friendly source, emerging as a promising alternative. However, the low solubility of these materials is, in many cases, a limitation to their use, especially in annual crops. For example, da Silva *et al.* (2017), using a biotite rock (17.7% K_2O), found a solubilization of only 39.54 mg dm^{-3} after 72 days of incubation. Ramos *et al.* (2022) reports a dissolution ranging from 10 to $20 \text{ mol m}^{-2} \text{ s}^{-1}$ for silicate minerals, such as feldspar, microcline, orthoclase.

Furthermore, the most efficient management of K in the soil is not only related to the sources or doses used but also to other aspects of agricultural soil management, such as organic matter content, compaction, soil biological activity, use of cover crops, and crop rotation (Alfaro *et al.*, 2004; Andrews *et al.*, 2021). Indeed, tropical soils are highly susceptible to K loss, especially through leaching and erosion (Flores *et al.*, 2022). Among these, the use of cover crops is a particularly effective method for promoting the improvement of soil's overall characteristics (Schjoerring *et al.*, 2019).

Cover crops have the ability to cycle nutrients, recovering elements lost in deeper layers of the soil (such as K itself), biological nitrogen fixation (leguminous plants), and the supply of organic matter, which promotes chemical, physical, and biological soil, in

addition to the large production of plant biomass that protects the soil surface, increasing water infiltration, and reducing the risk of erosion (Adetunji *et al.*, 2020). Among cover plants, it is worth highlighting the use of plants from the genus *Urochloa* and *Crotalaria*. Regarding the first, they have a great capacity for producing plant biomass, promoting K cycling, increasing the organic matter content of the soil, and inhibiting weed emergence (Adetunji *et al.*, 2020). Furthermore, more recently, it was demonstrated that the use of the species *U. decumbens* increases the agronomic efficiency of K application via phonolitic rock through its faster solubilization (da Rocha Neto *et al.*, 2024). In turn, species of *Crotalaria*, such as *C. juncea*, *C. spectabilis*, and *C. ochroleuca*, belong to the Fabaceae family and could establish symbiotic relationships with bacteria of the genus *Rhizobium* sp. and *Bradyrhizobium* sp., which promote biological nitrogen (Adetunji *et al.*, 2020). In addition, it has been shown that bacteria commonly associated with the *Crotalaria* root system can promote the solubilization of rock powders. For example, the use of bacteria *Rhizobium* sp. increased the phosphate solubilization from a rock powder by more than 50 times (Ferreira *et al.*, 2023).

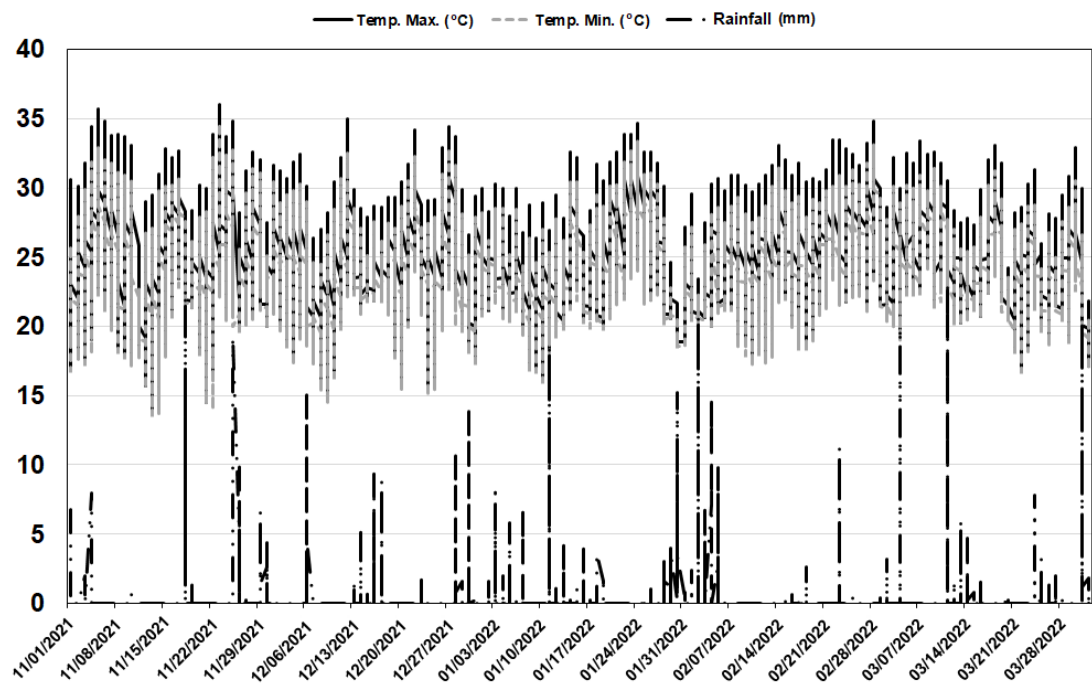
In tropical regions, to improve and optimize soil use, it is common to use intercropping between a grain-producing species and a cover crop. The planting of corn together with grasses of the *Urochloa* genus is the most common combination. However, there is an increase in areas intercropped with plants of the *Crotalaria* species, especially with the aim of making nitrogen available.

In view of the, our study aimed to assess potassium silicate as an alternate source of K in two production system, corn monoculture or intercropped with *Urochloa ruziziensis* or *Crotalaria spectabilis*.

2 METHODOLOGY

The study was conducted at the "Marcelo Mesquita Serva" Experimental Farm of Marília University, São Paulo State, in 2021, during the spring-summer season. According to the Köppen classification, the region's typical climate is humid subtropical (Cwa), characterized by dry, warm winters and hot, rainy summers. Climatological data were obtained from the National Institute of Meteorology (Figure 1).

Figure 1. Climate data from the experimental site during project implementation.



Source: Prepared by the authors, 2026.

The soil is classified as Ultisol (Santos *et al.*, 2006). Prior to the experiment's establishment, soil samples were collected from a depth of 0-20 cm for chemical fertility analysis (Raij *et al.*, 1997). The results of the soil analysis are presented in Table 1.

Table 1. Soil analysis of the experimental area.

pH	P resin	S	K	Ca	Mg	Al	H+Al	M.O.	SB	T	V	m
	mg dm ⁻³				mmol _c dm ⁻³			g dm ⁻³	mmol _c dm ⁻³		%	
5.0	10	5	1.6	19	7	1	22	19	27.6	49.60	55.6	3.5

Source: Prepared by the authors, 2026.

The experimental design was a randomized block setup in a 3x3 factorial scheme with split plots and four replications. The treatments were a combination of cover crops (single corn, intercropping with *Urochloa ruziziensis*, and intercropping with *Crotalaria spectabilis*) in the main plots, and K sources (no K, potassium chloride, and potassium silicate (Table 2)) in the subplots, totaling nine treatments. Each main plot consisted of four rows, each 18 meters in length, while the subplots comprised four rows, each six meters long. The two central rows of each subplot were designated as the effective area, with one meter at each end excluding from the measurements.

Table 2. Characterization of potassium fertilizers used in the experiment.

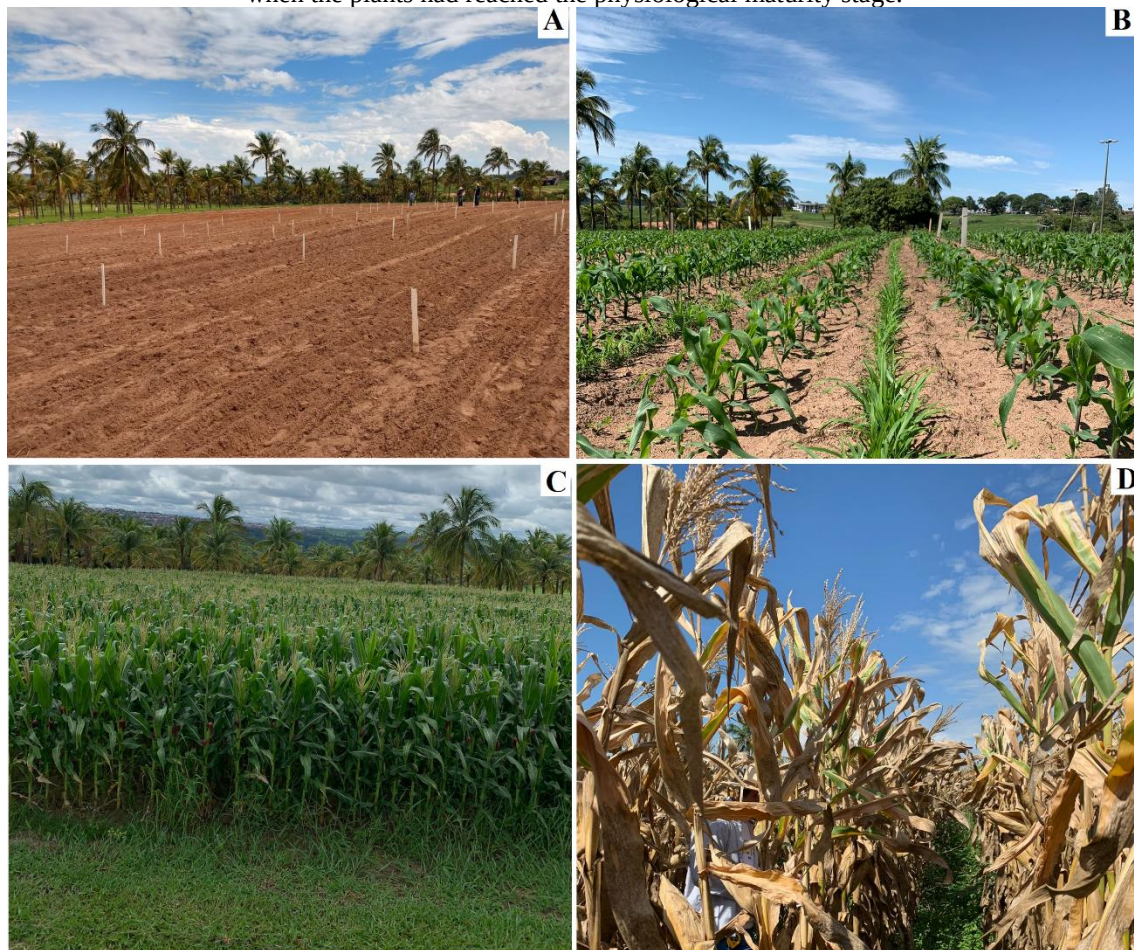
Contents	Potassium chloride (KCl)*	Potassium silicate (K6)*
	%	
K ₂ O	60	6,07
Cl	40	-
SiO ₂	-	65,7
MgO	-	1,12
CaO	-	2,62

* Product approved by Ministry of Agriculture, Livestock and Supply (MAPA).

Source: Prepared by the authors, 2026.

The experiment was initiated on December 2, 2021, using the hybrid Santa Helena 7990 PRO2. During sowing, planting fertilization was performed with simple superphosphate according to the recommendations of Bulletin 100 (Raij *et al.*, 1997). A row spacing of 0.90 m was used for the corn, and when necessary, the seeds of the cover crop were manually sown in a furrow between the corn rows. For brachiaria, *Urochloa ruziziensis* seeds were used to achieve a density of 350 cultural value points per hectare, calculated as $((\% \text{ germination} \times \% \text{ purity})/100)$. The *Urochloa ruziziensis* seeds had 85% germination and 80% purity, resulting in a cultural value of 68. To reach 350 cultural value points per hectare, 5.1 kg ha⁻¹ of seeds were used. For *Crotalaria spectabilis*, 20 kg ha⁻¹ of seeds with 90% germination were used. The cover crops were also sown on December 2, 2021 (Figure 2).

Figure 2. Overview of the experiment with intercropped or single corn and potassium sources. A) day of experiment implementation. B) detail of corn plant development and intercropped brachiaria in the interrow space. C) detail of the corn plants during the tasseling stage. D) time of experiment evaluation when the plants had reached the physiological maturity stage.



Source: Prepared by the authors, 2026.

For nitrogen fertilization, 100 kg ha^{-1} of N in the form of urea was applied, split into two applications (V4 and V7 stages). Potassium fertilization followed the recommendations of Bulletin 100, with manual surface application of different potassium sources 20 days after sowing, except for the control plants, which did not receive any potassium fertilization.

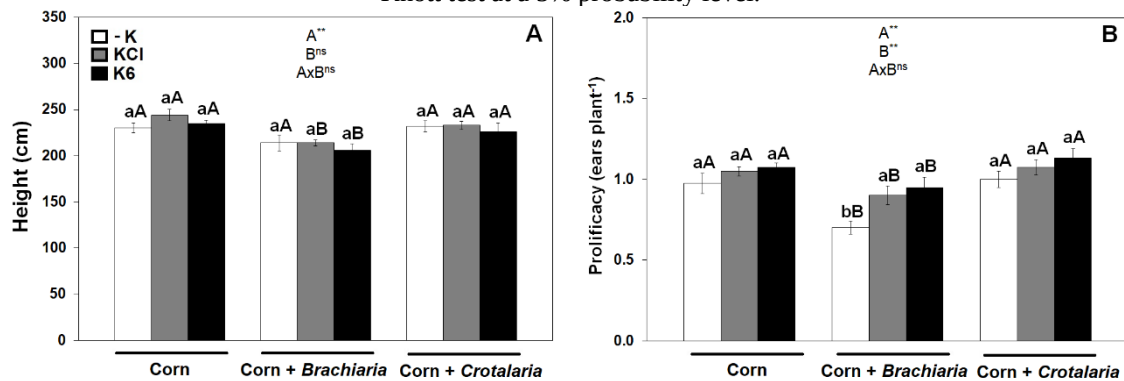
All evaluations were performed at the end of the corn cycle (116 days). Plant height was measured using a graduated tape. Prolificacy was assessed by counting the number of ears per plant. The ears from the plants in the effective area were then harvested, and ear length was measured using a graduated ruler, along with the number of rows per ear, grain weight per ear, and the weight of 100 grains. From these data, the grain weight per plant and yield in kg ha^{-1} were calculated. It is important to note that

grain moisture was standardized to 13%. Additionally, the dry matter yield of the intercropped crops, as well as of weeds, was evaluated separately (using a forced-air oven at 65°C for 72 hours), with the results extrapolated to kg ha⁻¹. The results were subjected to analysis of variance (ANOVA) using the F test and when significant ($p \leq 0.05$), the means were compared using the Scott-Knott test ($p \leq 0.05$). Statistical analyses were performed using the AGROESTAT® software (Barbosa & Maldonado, 2015).

3 RESULTS AND DISCUSSIONS

Plant height was influenced solely by intercropping (Figure 3A). Corn plants intercropped with *Brachiaria* and fertilized with either KCl or K6 exhibited reduced height compared to both monoculture plants and those intercropped with *Crotalaria* (Figure 3A). However, the sources of potassium did not affect plant height (Figure 3A). In contrast, prolificacy was impacted by both intercropping and potassium sources (Figure 3B). Similar to the height results, plants intercropped with *Brachiaria* showed reduced prolificacy, regardless of the potassium source used (Figure 3B). Although monoculture plants and those intercropped with *Crotalaria* exhibited the highest prolificacy, no significant difference was observed between these two groups (Figure 3B). Additionally, plants intercropped with *Brachiaria* that did not receive potassium fertilization demonstrated the lowest prolificacy (0.7 ears per plant) (Figure 3B).

Figure 3. Analysis of plant height (A) and prolificacy (B) of corn (cv. Santa Helena 7990 PRO2) in response to intercropping (monoculture; Brachiaria: *Urochloa ruziziensis*; Crotalaria: *Crotalaria spectabilis*) and different potassium sources (-K: no potassium; KCl: potassium chloride; K6: potassium silicate). Data are presented as mean $\pm$ standard error ($n = 4$). Capital letters within the vertical bars indicate significant differences between intercropping systems for the same potassium source, while lowercase letters compare potassium sources within the same intercropping, as determined by the Scott-Knott test at a 5% probability level.



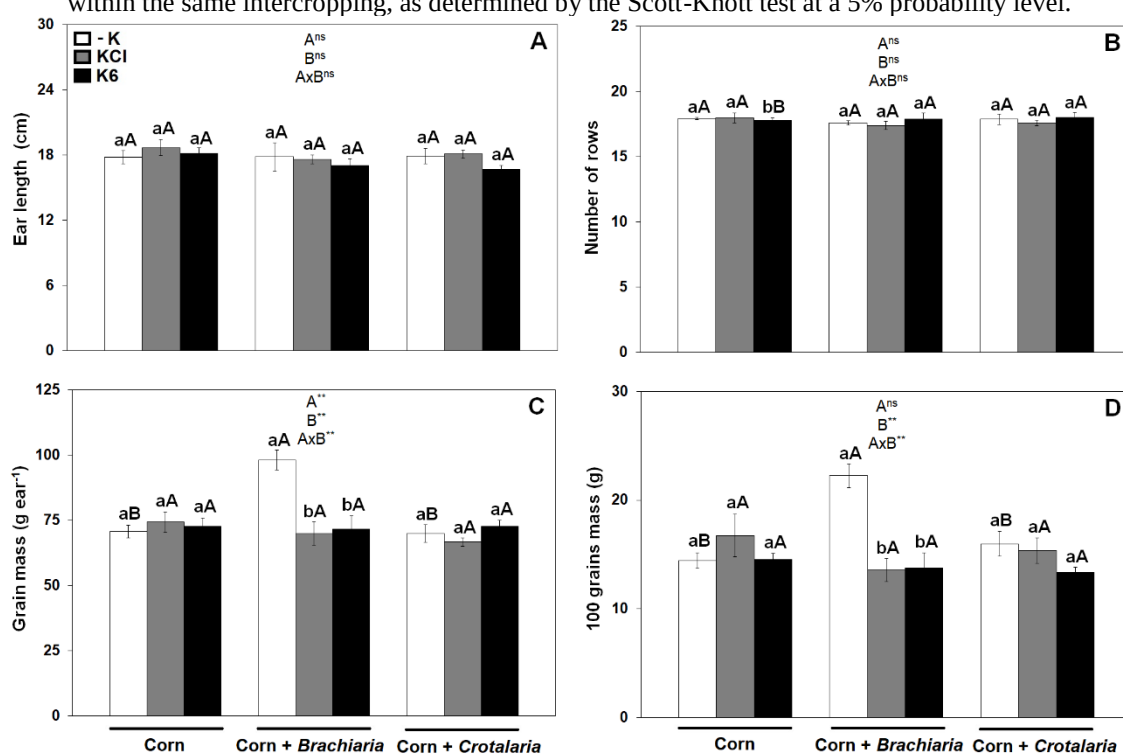
Source: Prepared by the authors, 2026.

Numerous studies have documented that intercropping corn with Brachiaria can negatively impact the development and productivity of corn due to competition between the two species (Lima *et al.*, 2020; Silva *et al.*, 2020). For instance, Lima *et al.* (2020) reported significant reductions in the growth of corn plants intercropped with *Urochloa ruziziensis*. Additionally, corn productivity can decrease by more than 30% when intercropped with *U. ruziziensis* (Silva *et al.*, 2020). However, the negative effects of this competition can be mitigated by suppressing the initial growth of Brachiaria using sub-lethal doses of herbicides such as nicosulfuron, mesotrione, or even glyphosate (Lima *et al.*, 2020). This explains the lower height and prolificacy observed in corn plants intercropped with Brachiaria.

The length of the ears was not affected by either the intercropping system or the potassium sources evaluated in this experiment (Figure 4A). However, the number of rows was negatively impacted by K6 fertilization in monoculture corn, resulting in fewer rows compared to other potassium sources under the same conditions or to K6 use in corn intercropped with Brachiaria or Crotalaria (Figure 4B). The average ear length was 17.75 cm, and the average number of rows was 17.8 (Figures 4A and 4B). On the other hand, both grain mass per ear and 100-grain weight showed a similar pattern, being influenced by both intercropping and potassium fertilization (Figures 4C and 4D). Notably, corn plants intercropped with Brachiaria and without potassium fertilization exhibited higher

grain mass per ear and 100-grain weight compared to monoculture plants or those intercropped with *Crotalaria* (Figures 4C and 4D). Among the plants intercropped with *Brachiaria*, the absence of potassium fertilization also resulted in higher grain mass per ear and 100-grain weight when compared to plants fertilized with KCl or K6 (Figures 4C and 4D). Potassium sources did not affect these parameters in monoculture corn or in corn intercropped with *Crotalaria* (Figures 4C and 4D).

Figure 4. Analysis of ear length (A), number of rows per ear (B), grain mass per ear (C), and 100-grain weight (D) of corn plants (cv. Santa Helena 7990 PRO2) in response to intercropping (corn monoculture; *Brachiaria*: *Urochloa ruziziensis*; *Crotalaria*: *Crotalaria spectabilis*) and different potassium sources (-K: no potassium; KCl: potassium chloride; K6: potassium silicate). Data are presented as mean $\pm$ standard error ($n = 4$). Different uppercase letters within the vertical bars indicate significant differences between intercropping systems for the same potassium source, while lowercase letters compare potassium sources within the same intercropping, as determined by the Scott-Knott test at a 5% probability level.

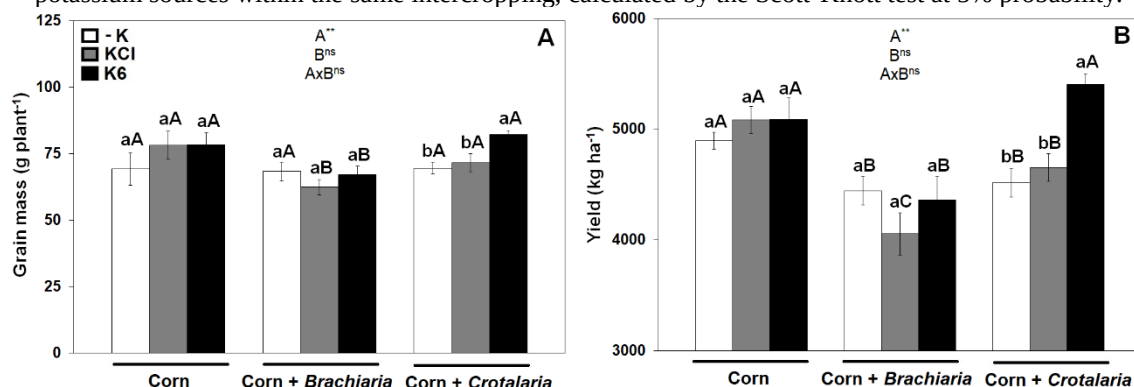


Source: Prepared by the authors, 2026.

Interestingly, corn plants intercropped with *Brachiaria* and that did not receive potassium fertilization showed the highest values of grain mass per ear and 100 grains (Figures 4C and 4D). However, these data can be explained mainly by the lower prolificacy of these plants (Figure 3B). Thus, the available photoassimilates could be redistributed to a smaller number of ears per plant or grains, which allowed greater accumulation of dry mass in them.

Grain production was influenced by both the intercropping system and the potassium sources (Figure 5). For instance, grain production per plant was significantly lower when plants fertilized with KCl or K6 were intercropped with Brachiaria, compared to monoculture plants or those intercropped with Crotalaria (Figure 5A). Additionally, plants intercropped with Crotalaria were more productive when K6 was used as the potassium source, producing 83.1 g per plant, which was significantly higher than with KCl or no potassium under the same intercropping conditions (Figure 5A). Regarding overall productivity, the lowest yield was observed in plants treated with KCl and intercropped with Brachiaria (4,055 kg ha⁻¹). When KCl was used as the potassium source, the highest yield was achieved by monoculture plants (5,088 kg ha⁻¹) (Figure 5B). Plants not fertilized with potassium showed higher productivity when not intercropped (4,896 kg ha⁻¹), while the lowest productivity was observed in plants intercropped with Brachiaria or Crotalaria, producing 4,444 kg ha⁻¹ and 4,518 kg ha⁻¹, respectively (Figure 5B). The highest yield was obtained by plants intercropped with Crotalaria and fertilized with K6 (5,404 kg ha⁻¹), though this was not significantly different from monoculture plants (5,088 kg ha⁻¹) (Figure 5B).

Figure 5. Grain mass (A) and productivity (B) of corn cv. Santa Helena 7990 PRO2 in response to intercropping (corn monoculture; Brachiaria: *Urochloa ruziziensis*; crotalaria: *Crotalaria spectabilis*) and different potassium sources (-K: without potassium; KCl: potassium chloride; K6: potassium silicate). Data show means $\pm$ standard error (n = 4). Different capital letters in the vertical bars indicate significant differences between intercropping for the same potassium source, while lowercase letters compare potassium sources within the same intercropping, calculated by the Scott-Knott test at 5% probability.



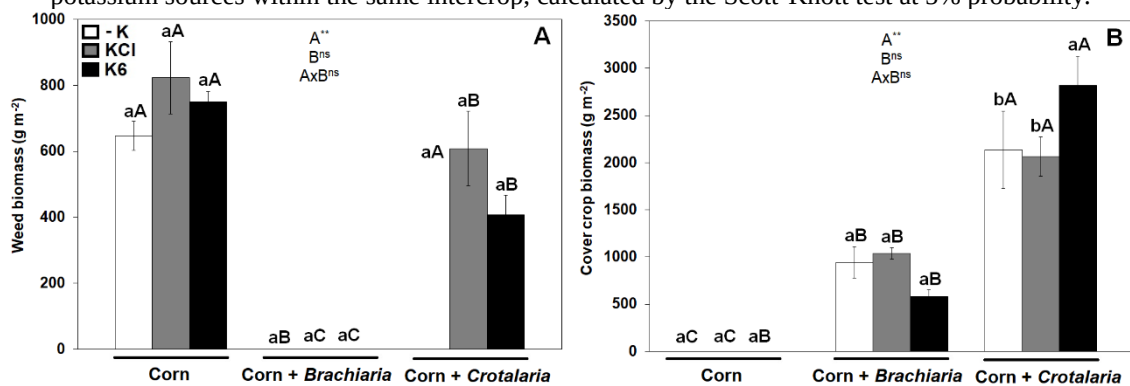
Source: Prepared by the authors, 2026.

Once again, the negative effect of intercropping Brachiaria with corn plants is evident by the reduced grain mass per plant, except in plants not fertilized with potassium, and by the lower productivity compared to monoculture plants (Figure 5). Productivity

was also negatively affected by intercropping with *Crotalaria* in plants without potassium and those fertilized with KCl (Figure 5B). On the other hand, the highest productivity was achieved by corn plants intercropped with *Crotalaria* and receiving K6 as the potassium source, although this was not significantly different from monoculture plants. Furthermore, potassium fertilization did not influence grain mass per plant or productivity, except in plants intercropped with *Crotalaria*. This can be explained by the potassium availability in the soil (Table 1). The soil used in this experiment had a potassium level of $1.6 \text{ mmolc dm}^{-3}$, according to Cantarella *et al.* (2022). Although this level is at the critical threshold, it is still within the adequate range for cultivation of corn. Thus, even treatments that did not receive potassium fertilization had their needs met by the potassium present in the soil (Mengel *et al.*, 2001).

The biomass of weeds at the end of the experiment was not influenced by potassium fertilization (Figure 6A). On the other hand, intercropping significantly reduced the presence of weeds (Figure 6A). For example, the use of *Brachiaria* completely eliminated the presence of weeds in the area, while *Crotalaria* only reduced weed presence when combined with the use of KCl and K6 (Figure 6A). As expected, non-intercropped areas had the highest weed biomass (Figure 6A). Regarding cover crop biomass, *Brachiaria* produced the lowest biomass, especially when K6 was used as a fertilizer, compared to *Crotalaria* (Figure 6B). In addition to producing the highest biomass, *Crotalaria* also responded positively to K6 as a potassium source, achieving $2,820 \text{ g m}^{-2}$ of biomass (Figure 6B).

Figure 6. Plant biomass (A) and cover crop biomass (B) under intercropping conditions with corn cv. Santa Helena 7990 PRO2 and different potassium sources (-K: without potassium; KCl: potassium chloride; K6: potassium silicate). Different capital letters in the vertical bars indicate significant differences between the intercrops for the same potassium source, while lowercase letters compare the potassium sources within the same intercrop, calculated by the Scott-Knott test at 5% probability.



Indeed, one of the most well-documented benefits of using *Brachiaria* as a cover crop is its ability to suppress weed populations. For example, São Miguel *et al.* (2018) observed that using *Urochloa ruziziensis* either alone or intercropped with corn provided excellent weed control in the area. *Brachiaria* has a strong suppressive effect on weeds due to its aggressiveness, rapid growth, shading of the area, and biochemical properties (Kobayashi & Kato-Noguchi, 2015; Macías *et al.*, 2019). Regarding the latter, the release of biochemical substances, a process known as allelopathy, such as protodioscins, has been associated with the inhibition of germination and development of weeds like *Ipomoea grandifolia* and *Digitaria insularis* (Menezes *et al.*, 2021).

Our results indicate that corn production was negatively affected by intercropping with *Brachiaria*, regardless of the potassium source, and when intercropped with *crotalaria* and fertilized with KCl or without K (Figure 5B). *Crotalaria* showed higher biomass production but was less efficient in suppressing weed development when compared to *Brachiaria* (Figure 6). The potassium sources provided contradictory results; however, when intercropped with *crotalaria*, the highest corn productivity was obtained using K6 (Figure 5B).

4 CONCLUSION

There is currently great pressure to adopt more sustainable and efficient agricultural practices. Indeed, integrated crop-livestock system provides several benefits to agricultural production systems, such as greater land use efficiency, soil and water conservation, and improved chemical, physical, and biological soil properties. One of the most common practices in IPS is the use of intercropping to diversify the area. Thus, our study demonstrates that the use of *Urochloa ruziziensis* has a high potential for competition with corn, while the use of *Crotalaria spectabilis* provided lower risks of competition. Furthermore, although the results were not clear regarding the use of potassium sources, when corn was intercropped with *C. spectabilis*, the use of potassium silicate resulted in productivity gains.

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