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# Improving potassium use efficiency of sugarcane through the use of polyhalite

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## Abstract

**Background:** Sugarcane (*Saccharum officinarum*) is an important crop in the production of food and energy in tropical and subtropical regions. To provide plants with what they need, highly concentrated fertilizers are often deployed which can result in imbalances in plant nutrition. The purpose of this study was to assess the efficiency of polyhalite ( $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$ ) as an alternative source of multinutrients for sugarcane compared to single sources of K, Ca, Mg and S.

**Methods:** A glasshouse experiment was carried out on a low-K Entisol from the sugarcane cultivar CV7870. A completely randomized design was used with different K fertilizer management strategies as follows: four K dosages (0, 21, 42 and 63 mg dm<sup>-3</sup>) associated to distinct sources, namely: polyhalite (PHY); potassium chloride (KCl); potassium chloride+polyhalite in a 1:1 ratio (½KP), and potassium chloride combined with phosphogypsum and kieserite balancing Ca, Mg and S dosages as supplied by pure polyhalite (KGK). Two growth cycles in 6 dm<sup>3</sup> soil pots were evaluated: cane plant harvested at 131 days after transplanting, and ratoon harvested at 253 days after transplanting for the determination of dry matter production. Immediately before harvesting in both cycles, leaf nutrient content (K, Ca, S and Cl) was determined using a hand-held X-ray fluorescence spectrometer.

**Results:** In general, shoot dry matter and nutrient uptake were higher with the highest K dosage applied and K sources containing Ca and S in the formulation PHY; ½KP; and KGK, for both growth cycles. However, when these sources were provided at the lowest dosage, high agronomic efficiency was observed in all nutrients assessed. Consequently, the cultivar CV7870 was responsive to K application. However, increments in the K dosage resulted in low agronomic efficiency.

**Conclusions:** This study indicates that PHY is an effective fertilizer for sugarcane farmers seeking to improve nutrient uptake in a low-K Entisol for both cane plant and ratoon. A mix of PHY and KCl is a potential multi-nutrient fertilizer for managing sugarcane production.

**Keywords:** Agronomic efficiency, Balanced nutrition, Calcium, Magnesium, Potassium, *Saccharum officinarum*, Sulfur

## Background

In sugarcane (*Saccharum officinarum* L., Poaceae), K is an essential element with the highest absorption levels and export (Filho 1993), found mainly in the ratoon cycles (Korndörfer and Oliveira 2005), on account of the role they play in the transporting of sugars (Cai et al. 2012), nitrogen metabolism, water absorption and transport, osmoregulation, enzyme activation and load neutralization (Römheld and Kirkby 2010). Thus, K is

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crucial to the maintaining of sugarcane yields (Paneque et al. 1992). Brazil is the world's largest sugarcane producer (FAO 2021), with an estimated stalk production of approximately 568.4 million tons from 8.26 million hectares in the 2021/2022 growing season (CONAB 2021). Despite the large crop area, the average stalk yield continues to be low, approximately 68.78 Mg ha<sup>-1</sup> (CONAB 2021).

This low average yield of sugarcane is most likely responsible for the recent agricultural expansion into new areas with low fertility and acidic soils (Bernardo et al. 2019; Bordonal et al. 2018). Brazil is the country with the largest area of acidic soil (Vitorello et al. 2005), where Entisols alone account for approximately 50 million hectares of the country's surface area (Spera et al. 1999; Santos et al. 2011).

Additionally, in highly weathered tropical soils, K dynamics are complex due to their low concentration in parental material and fixation in the structure of 2:1-layer silicate minerals (Conti et al. 2001; Santos et al. 2015). Thus, the use of mineral fertilizers has become mandatory for production in Brazil, making this country the world's second largest consumer of K, in the form of potassium chloride (KCl) as the most widespread potassium-bearing fertilizer in sugarcane production (ANDA 2017). To compensate for its drawbacks in the context of agricultural sustainability, studies on the rational use of fertilizers has become a critical issue, since this accounts for a large portion of production costs (Cortez et al. 2010).

Other elements essential to improving sugarcane yield are calcium (Ca), magnesium (Mg) and sulfur (S). Calcium is essential to cell wall stabilization and strengthening, as well as to the regulation of membrane permeability and cell division (Oliveira et al. 2018). Furthermore, magnesium is the core atom of the chlorophyll molecule, and it is required as an enzyme promotor in protein synthesis by bridging ribosome subunits (Garcia et al. 2020). Sulfur is a necessary component of amino acids, and thus proteins, as well as instrumental in the formation of coenzymes. It is also required for the activity of nitrate reductase and the production of chlorophyll (Singh and Tiwari 2018).

An alternative multi-nutrient source emerging on the world fertilizer market is polyhalite (PYH), an evaporite mineral found in marine sedimentary deposits, described by the chemical formula  $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$  equivalent to 13.0% K, 13.3% Ca, 4.0% Mg, and 21.3% S (Manning, 2017). The use of PYH for agricultural purposes began when a deposit of commercial size was discovered in the early twentieth century in New Mexico and western Texas, United States (Hoots 1925; Mansfield and Lang 1929) and reported in some countries, such

as Austria (Stromeyer 1820), Germany (Schober 1868), France (Cloizeaux 1867), Italy (Cortese 1922), Russia (Kurnakov et al. 1937), Poland (Buyalov and Lepeshkov 1937) and India (Gohil et al. 1996). However, commercial interest was abandoned after the discovery of a huge deposit of sylvinite (KCl.NaCl) in Saskatchewan, Canada.

Recently, since the discovery of Zechstein deposits located in North Yorkshire, in the United Kingdom, the world's largest highest grade deposit of PYH (Kemp et al. 2016), it has again aroused interest in the use of this mineral as fertilizer, promoting new research on crops such as rape oilseed (Dugast 2015), mustard (Tiwari et al. 2015), cabbage and cauliflower (Satisha and Ganeshamurthy 2016), peanut (Hoang et al. 2016), tea (PVFCCo 2016a; Zhou et al. 2019), coffee (PVFCCo 2016b), potato (Mello et al. 2018a), tomato (Mello et al. 2018b, 2019), corn (Pavuluri et al. 2017; Molin et al. 2019) and alfalfa (Bernardi et al. 2018). Taken together, these studies indicate that PYH is as effective as KCl or K<sub>2</sub>SO<sub>4</sub>, that provides a slower release of nutrients to plant growth. However, few of these studies balanced S, Ca and Mg concentrations similar to PYH treatments (Barbarick 1991; Mello et al. 2018a, b), avoiding negative plant responses derived from Ca, Mg or S not provided by non PYH treatments.

In view of the above, research into K dynamics in weathered tropical soils under PYH fertilization, pertaining to K availability and uptake by sugarcane, is still limited in the literature. Therefore, this study aimed to evaluate the agronomic performance of PYH in both cane plant and ratoon as a multi-nutrient source for sugarcane on a low-K Entisol contrasting with a single K fertilizer source (potassium chloride) combined with Ca, Mg and S sources (phosphogypsum and kieserite).

## Methods

### Pot experiment with sugarcane

The experiment was conducted in a glasshouse at the Luiz de Queiroz College of Agriculture (ESALQ/USP), Piracicaba-Brazil (22°42'S, 47°38'W), with an average air temperature of 30/18 °C (day/night) and relative humidity between 50 and 90%. The soil used was collected from the 0–20 cm layer of a native area in nearby sugarcane farms in Agudos-SP (22°33'S, 49°06'W), and was classified as Entisol (Quartzipsamment) (Soil Survey Staff 2014) with 945, 17 and 38 g dm<sup>-3</sup> of sand, silt, and clay, respectively. Afterwards, the soil was air-dried and sieved in a 2 mm mesh, and physicochemical analysis was carried out for initial characterization of nutrient contents and texture as follows: pH(CaCl<sub>2</sub>): 4.4; organic matter: 8.0 g dm<sup>-3</sup>; available P: 6.0 mg dm<sup>-3</sup>; available K: 55.0 mg dm<sup>-3</sup>; exchangeable Ca: 120.0 mg dm<sup>-3</sup>; exchangeable Mg: 48.0 mg dm<sup>-3</sup>; and exchangeable acidity (H + Al): 235.0 mg dm<sup>-3</sup> (Raj et al. 2001).

Uniform stalks of the CV7870 sugarcane variety were collected from 8-month-old plant growth for the second season in the field in the same soil sampling location. Stalks were cut in stem-node segments for propagation in washed sand for 25 days. Afterwards, uniform seedlings were selected for transplanting into pots.

The experiment was set up in a completely randomized design with four replicates, in a factorial scheme with four K sources: KCl (pure), PYH (pure), 1/2KCl + 1/2PYH (1/2KP) and KCl + GYP + KIE (KGK); and three doses of K: 21, 42 and 63 mg dm<sup>-3</sup> soil (50, 100, and 150 kg ha<sup>-1</sup> K<sub>2</sub>O, respectively), with two additional controls: absolute control (no NPK fertilizer) and control (no K fertilizer) (Table 1). The experimental unit was a plastic (PVC) pot of 6 L capacity containing 6 dm<sup>3</sup> of soil (dry basis) and one sugarcane seedling. Plants were watered 3 times per week with deionized water to maintain soil moisture ~70% of the maximum soil water-holding capacity, based on the weight of random experimental units (n = 10), during the experimental period.

The treatments were applied to each experimental unit directly before transplanting, obtaining powdered formulations to mix the K treatments uniformly by shaking the soil in a plastic bag for 2 min. Additionally, powdered phosphate fertilizer (Monoammonium Phosphate-11% N, 52% P<sub>2</sub>O<sub>5</sub>) at a total rate of 150 mg dm<sup>-3</sup> P<sub>2</sub>O<sub>5</sub> (300 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>) was applied at that time. Nitrogen (N) was supplied as ammonium nitrate (30% N) in three applications: 30 mg dm<sup>-3</sup> of N (60 kg ha<sup>-1</sup> N) at transplanting and two topdressing applications of 15 mg dm<sup>-3</sup> of N (30 kg ha<sup>-1</sup> N) at 15 and 50 days after transplanting.

Nitrogen fertilizer was applied diluted in the irrigation water. For the treatments with KGK, the dosage was calculated to supply Ca, Mg and S and balanced according to the quantity supplied in the PYH (pure) treatments by using phosphogypsum and kieserite (Table 1). However, the Ca dosage was still lower than pure PYH. Micronutrients were provided at transplanting for all pots in the following amounts (mg dm<sup>-3</sup>): 5.0 Fe; 5.0 Zn; 4.5 Mn; 1.5 Cu; 0.3 B and 0.3 Mo.

After the first sugarcane cycle harvest (131 d) (cane plant), N fertilizer was applied again during the second cycle (ratoon) with top-dressing application at a dosage of 30 mg dm<sup>-3</sup> (60 kg ha<sup>-1</sup> N) per event, distributed in two applications at 15 and 30 days after harvest. Potassium treatments were not re-applied to evaluate its effect on ratoon. However, phosphate and micronutrients were not supplied during the second cycle.

**Sugarcane dry matter and nutrient content**

At 131 d after transplanting sugarcane plants were harvested by cutting the shoot at the soil surface. Afterwards, the shoot was oven dried at 60 °C for 72 h (constant weight) and weighed for determining dry matter (DM) production. The root system was left to allow regrowth simulating a field ratoon. The harvest of the second cycle was evaluated at 122 d after regrowth (253 days after transplanting), and the DM was similarly determined.

Immediately before the harvest in both cycles, leaf nutrient content (K, Ca, S and Cl) was identified by cutting the middle portion of the Top Visible Dewlap (TDV). Directly after cutting, the leaf sample was washed with

**Table 1** Treatments used as a multi-nutrient source of K in an acidic sandy Entisol for sugarcane development in a pot trial

Treatment <sup>a</sup>	Applied nutrient (mg dm <sup>-3</sup> ) <sup>b</sup>						
	K	Mg	S	Ca	N	P <sub>2</sub> O <sub>5</sub>	Cl
Absolute control	0	0	0	0	0	0	0
Control (N+P)	0	0	0	0	120	150	0
KCl 21	21	0	0	0	120	150	19
KCl 42	42	0	0	0	120	150	38
KCl 63	63	0	0	0	120	150	57
PYH 21	21	6.5	34	21.5	120	150	0
PYH 42	42	13	68	42	120	150	0
PYH 63	63	20	102	63	120	150	0
KGK 21	21	6.5	34	17.5	120	150	19
KGK 42	42	13	68	35	120	150	38
KGK 63	63	20	102	52.5	120	150	57
1/2KP 21	21	3.3	17.5	10.5	120	150	9.5
1/2KP 42	42	6.6	34	21	120	150	19
1/2KP 63	63	9.9	51.5	32	120	150	28.5

<sup>a</sup> PYH Polyhalite, KCl Chloride of potassium, GYP phosphogypsum, KIE kieserite, KCl + GYP + KIE = KGK; 1/2KCl + 1/2PHY = 1/2KP

<sup>b</sup> Ca, Mg and S in KCl treatments are applied by means of kieserite and phosphogypsum.

deionized water and dried with a clean towel paper before analysis. Next, the sample was placed into a hand-held X-ray fluorescence spectrometer, the DELTA Professional model (Olympus, USA) equipped with an Rh target X-ray tube and a 10 mm<sup>2</sup> silicon drift detector (SDD) operated at 15 kV and 200 μA. The dwell time was 90,000 ms. A docking station and a lead enclosure radiation shield were used. A randomly selected sampling spot in the interveinal region on the adaxial side of the TDV was analyzed in triplicate.

#### Data and statistical analysis

The effectiveness of each K source relative to the standard KCl was calculated from the yield response relationships using the Eq. (1):

$$\text{RAE}(\%) = [(Y_i - Y_0)/(Y_{\text{KCl}} - Y_0)] \times 100 \quad (1)$$

where,  $Y_i$  is the shoot DM yield in treatments with added K fertilizers (g pot<sup>-1</sup>);  $Y_{\text{KCl}}$  the shoot DM yield with potassium chloride (reference fertilizer, RAE=100%) treatment and  $Y_0$  the shoot DM yield without K fertilizer (absolute control).

The K, Ca and S uptake were calculated as the product of a K, Ca and S concentration and shoot DM yield, applying another Eq. (2):

$$\text{K, Ca or S uptake (mg shoot}^{-1}\text{)} = \text{K, Ca or S content (mg g}^{-1}\text{)} \times \text{DM yield (g shoot}^{-1}\text{)} \quad (2)$$

Agronomic efficiency (AE) of each nutrient was calculated according to Eq. (3):

$$\begin{aligned} \text{AE (mg mg}^{-1}\text{)} &= (\text{shoot DM yield with added nutrient fertilizers} \\ &\quad \text{(mg pot}^{-1}\text{)} \\ &\quad - \text{Shoot DM yield in absolute control} \\ &\quad \text{(mg pot}^{-1}\text{)}) \\ &\quad / \text{nutrient applied via fertilizer (mg pot}^{-1}\text{)} \end{aligned} \quad (3)$$

All data were submitted to Shapiro–Wilk's normality test and Bartlett's homogeneity test, and suitable transformations were generated using Box-Cox techniques (Box and Cox 1964). Outliers were identified by standard deviation analysis (Aguinis et al. 2013) and removed when needed before carrying out variance analysis (ANOVA). The data was submitted to a two-way ANOVA, in case of significance in the interaction between the K source in each dosage; and the effects of K dosages in each K source were compared by Duncan's multiple range test,

respectively. In the absence of interaction, the t test (LSD) was used to evaluate the isolated effect of sources, and the effect of the dosage was adjusted to a linear or quadratic regression model. Relative agronomic efficiency (RAE) was compared by Dunnett's test. Principal component analysis (PCA) was carried out and visualized using PAST, version 3.21 (University of Oslo, Norway).

All statistical analyses were carried out using PROC-GLM and PROC-MIXED in SAS statistical software version 9.3 (SAS Institute 2008) and the graphs and regressions by Sigma Plot (Systat Software, San Jose, CA). The determinations of statistical significance were based on a critical value of  $\alpha=0.10$ .

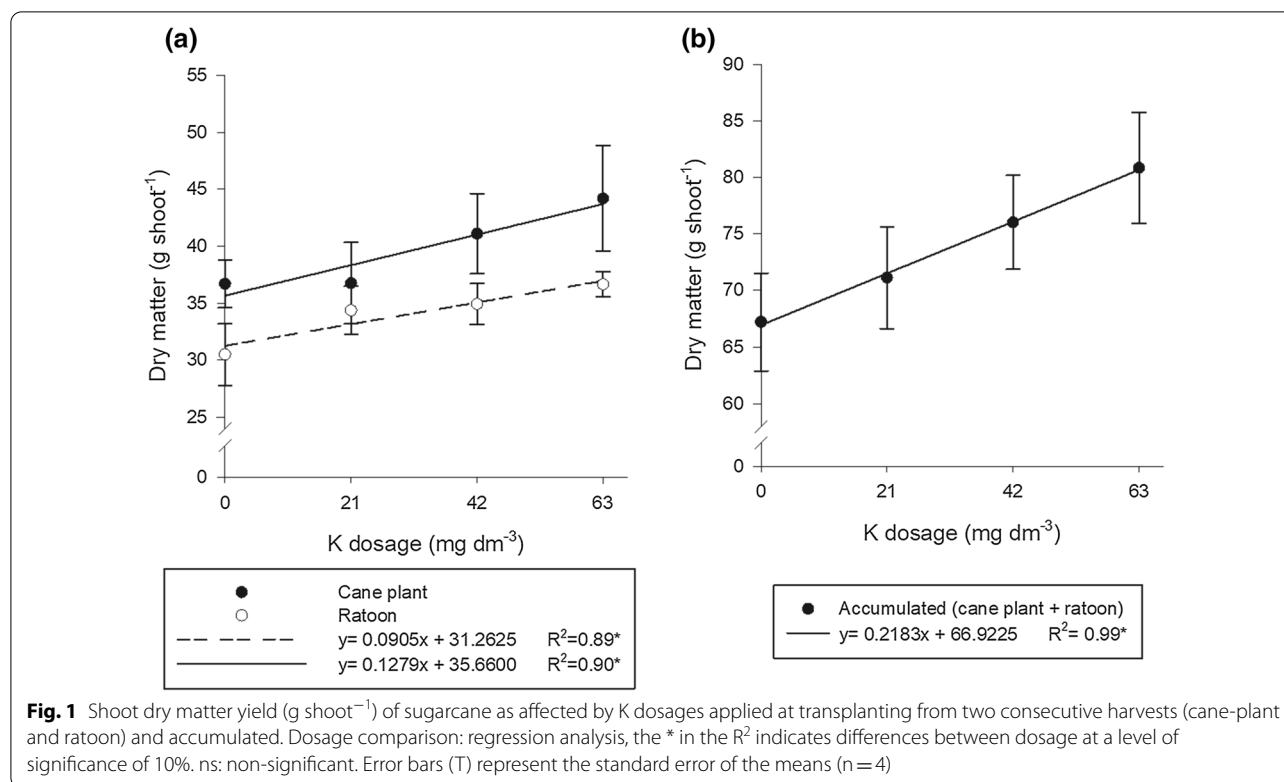
## Results

### Sugarcane response to fertilizer application

The shoot DM yield of sugarcane showed a linear adjustment influenced by K dosages, regardless of the source/formulation applied, for both the first (cane plant) and second cycle (ratoon) (Fig. 1). The first cycle (cane-plant) resulted in the highest DM in all treatments (mean 38.3 g shoot<sup>-1</sup>) compared to the ratoon crop (mean 33.5 g shoot<sup>-1</sup>). For the second growth cycle (ratoon), the residual of supplying K resulted in a 16% higher DM yield compared to control. Furthermore, lin-

ear increases in DM were observed when high K dosages were applied. For instance, for cane plant, every mg K dm<sup>-3</sup> applied increased 0,13 g shoot<sup>-1</sup> and 0,09 g shoot<sup>-1</sup> for ratoon. As regards the accumulated DM from both cycles, plants receiving no K fertilizer (absolute control and control N+P) produced 50 and 9 g shoot<sup>-1</sup> less than those receiving K fertilizer, respectively. Additionally, it increased according to the dosage of K application relative to control (5, 11 and 19% with 21, 42 and 63 mg K dm<sup>-3</sup>, respectively; Fig. 1b). The coefficient of variation was between 2 and 13%, showing low variability between replicates within each treatment.

In general, all leaf nutrient uptakes analyzed (K, Ca, S and Cl) were affected by K dosages and sources in an isolated way in both growth cycles of cane plant and ratoon. However, the latter showed a decline in uptake irrespective of the source and dosage supplied (Fig. 2). For K, the uptake was influenced by sources in cane-plant, with better results using PYH, KGK and ½KP than KCl, with mean values of 630, 607 and 656 mg shoot<sup>-1</sup> respectively (Fig. 2a), representing an average of 36% higher uptake compared to KCl treatment. However, in the ratoon, KCl together with ½KP, KGK and PYH achieved an average of 60% higher K uptake compared to control (N+P).



Dosage also influenced K uptake with a quadratic adjustment in the first growth cycle (Fig. 2a). A variation in K uptake under dosage compared to control in cane-plant was observed. Additionally, in ratoon the highest dosage (63 mg K dm<sup>-3</sup>) had promoted a significant increment in K uptake, with a mean value of 457 mg shoot<sup>-1</sup>, approximately 202% higher than that observed in the control (K0).

Sulfur uptake was affected by K dosage and sources, mainly in the first cycle, cane-plant (Fig. 2b). Thus, PYH exhibited the highest S uptake (150 mg shoot<sup>-1</sup>), whereas KCl did not have any variation compared to control (87 and 77 mg shoot<sup>-1</sup>, respectively). As regards the dosage, higher amounts of K fertilizer imply increments in S uptake in sugarcane. Based on this parameter, the following ranking was obtained: K63 > K42 > K21 > K0. No significant variation in the S uptake in ratoon crop was found for the treatments, no after effect of the sources over the time being reported.

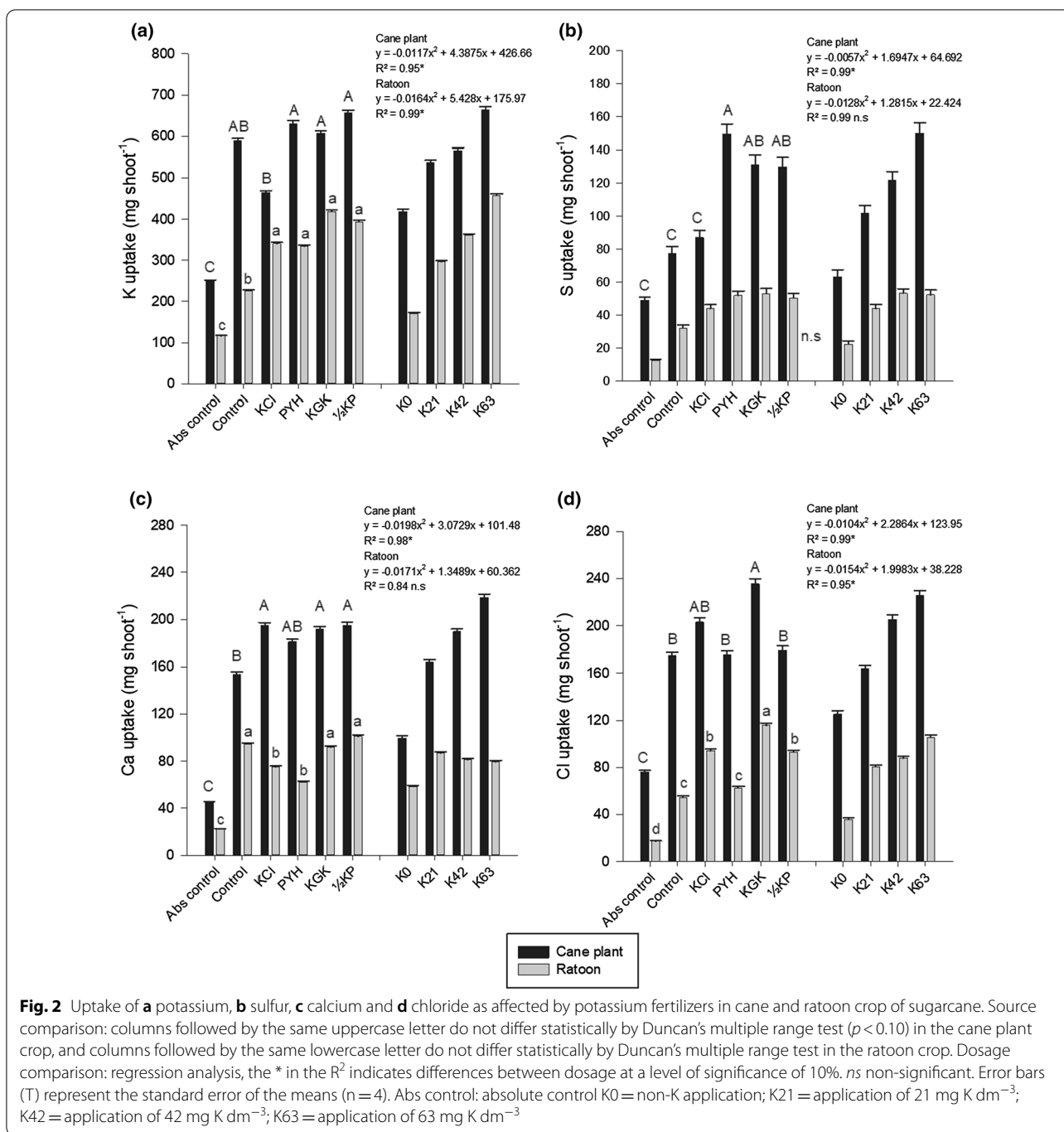
Calcium uptake was 400% lower under absolute control compared to the average of K dosages and sources in the cane-plant (Fig. 2c). In the ratoon cycle, PYH and KCl had lower Ca uptake compared to the ½KP and KGK formulations. Non-significant interactions ( $p > 0.10$ ) between sources were found in the cane-plant and between K dosages in the ratoon.

Chloride uptake was affected by K formulations and dosages. The largest increment in Cl uptake was observed under KGK in both growth cycles, cane plant and ratoon, approximately 235 and 116 mg Cl shoot<sup>-1</sup> respectively (Fig. 2d). In general, Cl uptake under PYH and ½KP were less expressive than pure KCl, achieving similar values to control in the cane plant; however, in ratoon only PYH reached similar Cl uptake compared to control. Additionally, all dosages applied significantly outperformed control treatments, exhibiting the after effect of fertilizers on Cl uptake by sugarcane.

## Discussion

### Sugarcane agronomic efficiency

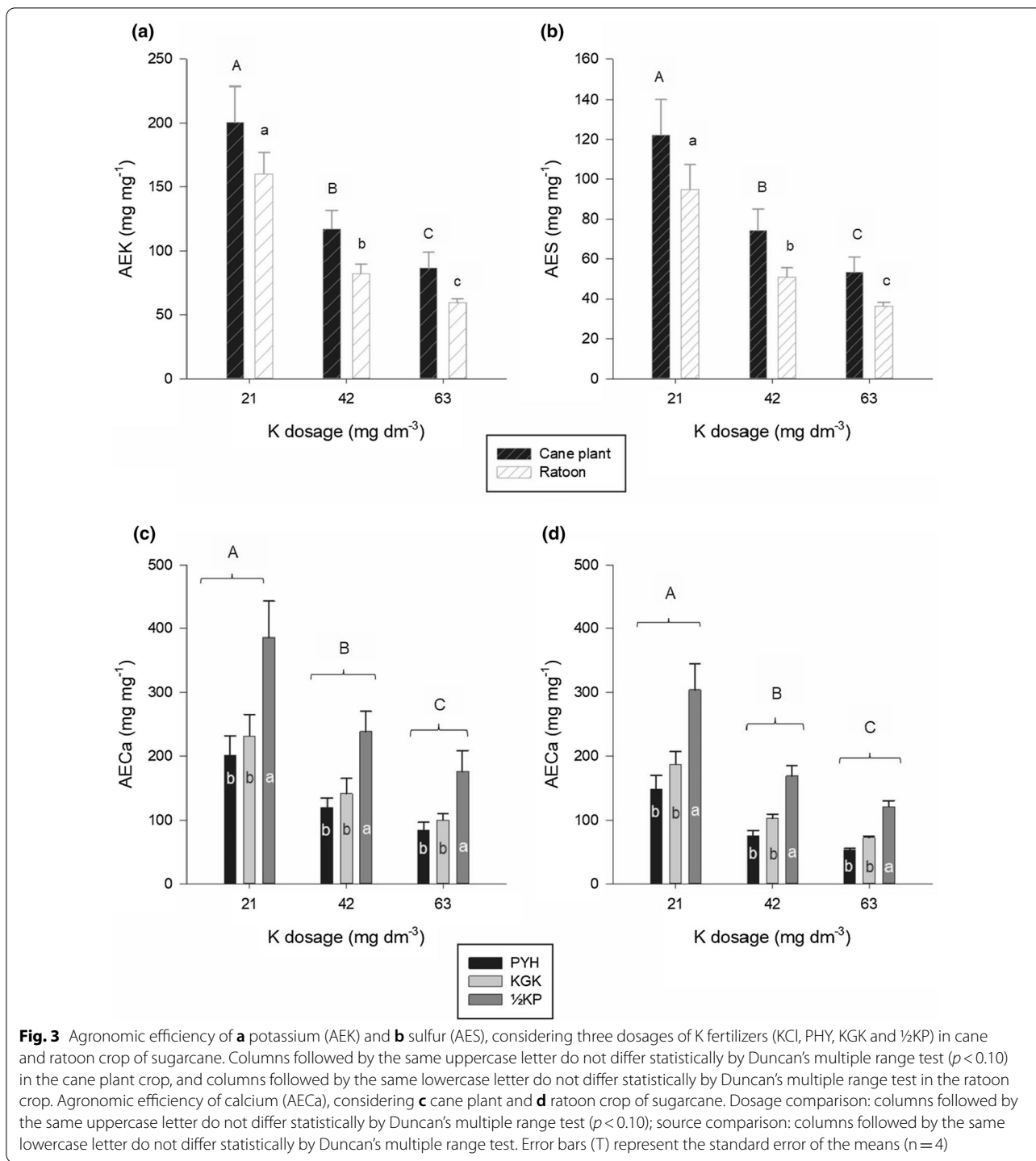
The relative agronomic effectiveness (RAE) of sugarcane was not significant depending on the source of K applied (Additional file 1: Fig. S1), indicating that PYH is similar to KCl for supplying nutrients for this crop. Moreover, RAE varied between 92 and 106%, which means that K formulations evaluated here were as efficient as the reference fertilizer irrespective of the growth cycle. Despite the critical indicators of low soil fertility in this study such as soil acidity and sandy texture, the use of PHY has the potential to sustainably increase sugarcane DM production and nutrient uptake. Similar results have been reported by Pavinato et al. (2020) and Bhatt et al. (2021), in acid and sandy soils, respectively. Additionally,



Barbarick (1991), assessing continuous cropping of sorghum-Sudan grass comparing PYH and other soluble sources of K, Ca, Mg and S in a glasshouse, noted that PYH was as effective as or superior to soluble fertilizers, as found in our study. Similarly, Yermiyahu et al. (2017) have reported similar findings, when evaluating the efficiency of PYH relative to equivalent soluble salts on wheat, where PYH was at least as good as the reference

fertilizers, also indicating that PYH is a good alternative K source for agriculture.

Agronomic efficiency of K (AEK) is presented in Fig. 3a. Supplying K in lower dosage resulted in higher AEK in both growth cycles, cane plant and ratoon, regardless of the K sources used. The dosage of 63 mg K dm<sup>-3</sup> reduced AEK by 2.3 times compared to the lowest



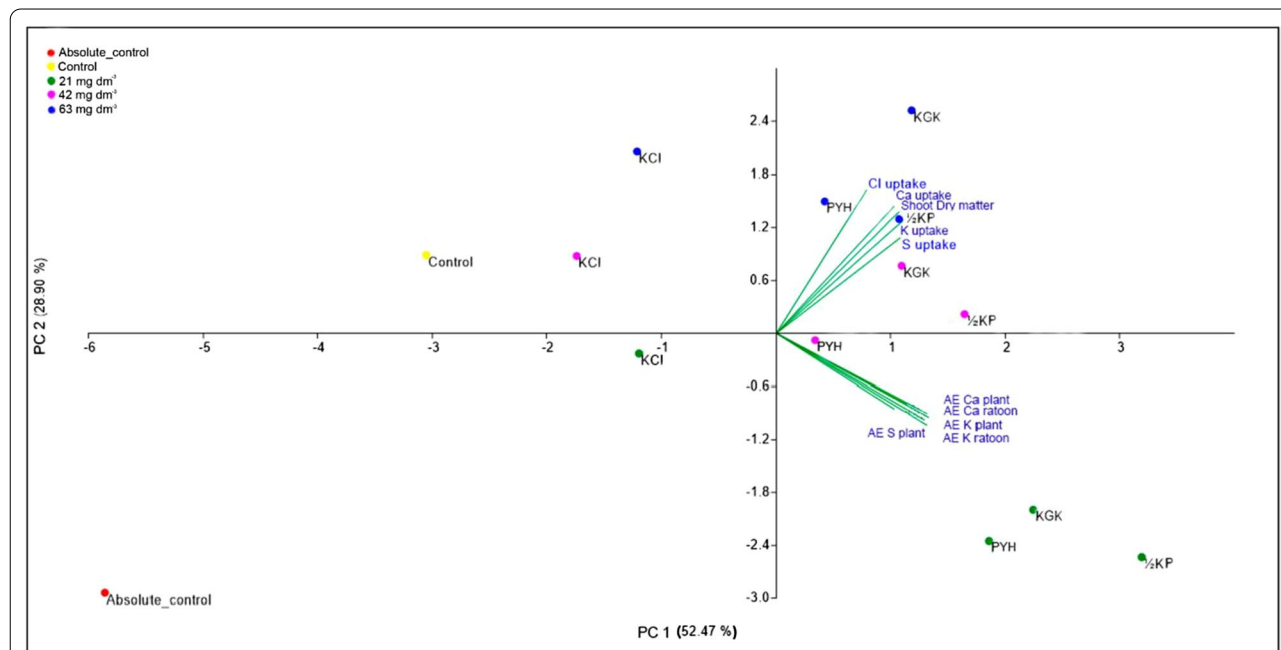
dosage used (21 mg K dm<sup>-3</sup>) in cane plant and approximately 2.6 times in ratoon. The AEK varied between 87 to 201 mg mg<sup>-1</sup> in cane plant and 59–160 mg mg<sup>-1</sup> in ratoon, averaging 135 mg mg<sup>-1</sup> and 101 mg mg<sup>-1</sup>, respectively. Comparing these results to K uptake (Fig. 2a), differences in plant response to K dosage can be explained

by the genetic potential of the sugarcane, since the variety CV7870 is adapted to more fertile soils, and is exceptionally responsive to K applications by increasing DM production but less agronomically efficient. Additionally, K uptake is more efficient than Ca or Mg on account of the effective H<sup>+</sup>/K<sup>+</sup> symport (a protein that transports

H<sup>+</sup> and K<sup>+</sup> ions simultaneously across root cell membranes) (Mengel et al. 2001). Kwong (2002) showed that most of the sugarcane K demand is absorbed before maximum dry matter accumulates, which is more concentrated over the maximum leaf area, and emphasizes the importance of a good initial K supply for positive whole cycle plant development. Similarly, Medina et al. (2013) reported higher K concentration in sugarcane at the beginning of plant development.

Considering the sources with S in their formulation (PYH, KGK and ½KP), the agronomic efficiency of sulfur (AES) varied significantly due to the dosage used, irrespective of sources in both growth cycles (Fig. 3b), indicating similar dynamics to AEK. The lowest AES was found on applying 63 mg K dm<sup>-3</sup>, with average values of 53 and 36 mg mg<sup>-1</sup> in cane plant and ratoon respectively, while under lower K dosages the AES increased progressively, obtaining the superior AES at 21 mg K dm<sup>-3</sup>, with mean values of 122 and 95 mg mg<sup>-1</sup> in cane-plant and ratoon respectively. Kaler et al. (2017) reported no S concentration response to elemental S fertilizer application rates of 0, 90, 224, 448 kg S ha<sup>-1</sup> in sugarcane, although the authors used a non-soluble source of S that may take several weeks to convert to a soluble form in the soil, whose behavior is completely different from a soluble source like PYH (Barbier et al. 2017), which solubilizes in days or weeks according to our results.

With regard to Ca in fertilizer formulations (PYH, KGK and ½KP), agronomic efficiency of calcium (AECa) was significantly affected by source and dosage though without any interaction in both cane plant and ratoon (Fig. 3c, d, respectively). Fertilization with ½KP increased AECa in the three dosages evaluated in both cane plant and ratoon. In contrast, when Ca was applied via PYH or KGK, the AECa was similar in both cane plant and ratoon regardless of the dosage used. Furthermore, AECa increased on account of K fertilization at the lowest dosage of K assessed. For instance, in cane plant under application of 21 mg K dm<sup>-3</sup> the AECa was two times higher than in the highest K dosage applied (Fig. 3c), and in ratoon this efficiency displayed the same performance as cane plant but in lower proportions (Fig. 3d). Contrasting Ca uptake and AECa, the application of sources using a multinutrient criteria demonstrates an improvement in DM yield of sugarcane which may indicate an adequate nutritional balance for plant growth. Calcium plays a key role in sugarcane physiology and is thus required for photosynthesis, carbon assimilation, and, as a result, dry matter production. This nutrient is also involved in secondary messenger signaling (Steinhorst and Kudla 2014), gene expression and protein regulation (Kudla et al. 2018), membrane permeability maintenance and regulation (Poovaiah and Leopold 1973), and the cross-linking and structural reinforcement of cell-wall constituents (Chan et al. 2017). Consequently, in addition to the



**Fig. 4** Principal component analysis (PCA) of accumulated K, S, Ca and Cl uptake, accumulated shoot dry matter and agronomic efficiency of K, Ca and S in sugarcane treated with three K dosages (21, 42 and 63 mg K dm<sup>-3</sup>) and four distinct sources/formulations. AE agronomic efficiency, acc accumulated



specific increase in Ca absorption in response to PHY, the critical role of Ca in sugarcane growth and development was highlighted.

In general, no significant relationship between DM and K, S, Ca and Cl content in leaves were detected. However, it was observed that most of the plants with leaf content below the critical level (McCray et al. 2013) were linked to ratoon cycle, probably experiencing a hidden hunger scenario. Additionally, shoot DM oscillated between 25 and 50 g, except for the absolute control (13 g). In this regard, plants derived from cane bud propagation exhibited sufficient concentrations of K, Ca and S for an initial development. However, higher dosages of K formulations applied led to luxury consumption suggesting that K, Ca, and S were not limiting crop development, irrespective of the K fertilizer source applied.

### Overview of sugarcane response to fertilization

As a general view among K dosage and sources/formulations, both cane plant and ratoon biomass production (DM) and accumulated nutrient uptake were correlated to high dosages applied and K sources containing Ca and S in the formulation (Fig. 4). A high foliar biomass is the basis of dry matter production and a requirement for the subsequent increase in sugar. Considering the accumulated results (cane plant and ratoon), the formulation  $\frac{1}{2}$ KP showed the highest K and Ca uptake and thus the highest DM yield, proving to be the best option for supplying K, Ca and S for sugarcane. The use of PHY as a complementary fertilizer can enhance the DM production (Chen et al. 2022). This condition is promoted as a result of reduced competition between  $\text{Cl}^-$  and  $\text{SO}_4^-$  for absorption by plant roots in the PHY, KGK; and  $\frac{1}{2}$ KP treatments when compared to sole KCl treatments where the presence of  $\text{Cl}^-$  and the lack of  $\text{SO}_4^-$  in the soil or the KCl fertilizer can make this competition more severe (Bhatt et al. 2021). However, when these sources were provided at the lowest dosage the highest correlation was observed with superior agronomic efficiency for all nutrients assessed (Fig. 4).

The two-component analysis explained 81.3% of the total variation among traits. Using the K dosage, the PCA was grouped into two main clusters: PHY, KGK; and  $\frac{1}{2}$ KP, applied at 42 and 63 mg K  $\text{dm}^{-3}$  which were in quadrant I and are characterized with high S, K, Ca and Cl uptake and, consequently, in highly accumulated shoot DM. In contrast, appearing in quadrant IV these sources supplied at the dosage of 21 mg K  $\text{dm}^{-3}$  yielded the highest agronomic efficiency for K, Ca and S, in both cane plant and ratoon. In quadrant II KCl, regardless of the dosage, and the control, was clustered demonstrating the similarity among them. Finally, the absolute control

is located isolated in the quadrant III, showing that non-application of these nutrients resulted in small uptake, poor shoot DM yield and agronomic inefficiency.

### Conclusions

Treatments containing K, Ca, and S in the formulation showed high agronomic performance, for both cane plant and ratoon. In this regard, using PHY on sugarcane is an alternative source of these nutrients in a single granule compared to single K source application. Indeed, the combination of KCl and PHY performs better than each source alone for sugarcane farmers. Nonetheless, there is still a need for more research into PHY application management, with an emphasis on lowered rates, improved ratios, and precise timing of application for each nutrient. Future research into the profitability of using PHY under field conditions is required.

### Abbreviations

GYP: Phosphogypsum; KIE: Kieserite; KCl: Potassium chloride; PHY: Polyhalite; XRD: X-ray diffraction;  $\mu$ -XRF: Micro X-ray fluorescence spectroscopy.

### Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s43170-022-00124-4>.

**Additional file 1: Fig. S1.** Relative agronomic effectiveness (RAE) of potassium fertilizers in cane and ratoon crop of sugarcane. For the K reference fertilizer, the potassium chloride (KCl), RAE=100% (cross hatched bars). Vertical bars (T) represent the standard error of the means ( $n = 4$ ). ns non-significant

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### Author contributions

WFBH devised the project, conducted the experiment, and wrote the first draft of the manuscript. BA performed the statistical analyses. HWPC supervised the  $\mu$ -XRF analysis and PSP supervised the project. All authors contributed to subsequent revisions, read, and approved the final manuscript. All authors read and approved the final manuscript.

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### Availability of data and materials

The datasets of this study will be available from corresponding authors on genuine request.

## Declarations

### Ethics approval and consent to participate

Not applicable. We did research on crop plant and did not handle animals along protected areas. Thus, no ethics protocol was required to be followed.

### Competing interests

The authors have no competing interests to declare.

### Consent for publication

Not applicable.

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