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Potato Response to Polyhalite as a Potassium Source Fertilizer in Brazil: Yield and Quality

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***Abstract*. Polyhalite (PH) is a hydrated sulfate evaporite mineral containing potassium, calcium, magnesium, and sulfur, nutrients all required in significant quantities by crops, but has limited evaluation as a fertilizer for potato (*Solanum tuberosum* L.). Fertilizer source and application rate field trials were conducted to evaluate PH as a fertilizer for potato production in the weathered tropical soils in Brazil. We selected two locations in the potato producing region of Southeast Brazil in 2015–16, one trial was conducted during the wet season at Tapira in São Paulo and the other during the winter season at Casa Branca in Minas Gerais. A common blend, 4–14–8, was made with either muriate of potash (MOP), sulfate of potash (SOP), or PH as the K source; with kieserite and gypsum added to the SOP to make a synthetic PH with similar composition; P either as single super phosphate (SSP) for the MOP blend or mono ammonium phosphate (MAP) for the PH and SOP blends; and N as urea adjusted for the N in MAP. All blends were applied at four application rates of 62, 125, 187, and 249 kg K/ha. A control was also included consisting of N and P as urea and MAP but no K, Ca, Mg, or S. Total and marketable yields as well as potato quality including dry matter, starch, soluble solids, hardness, and crunchiness were measured at harvest using standard techniques. At Tapira, potato yields increased linearly with increasing K application rate from 22.4 $t \cdot ha^{-1}$ for the control to the highest yield of 29.2 $t \cdot ha^{-1}$ and were higher for PH and SOP than MOP (28.8, 29.2, and 25.3 $t \cdot ha^{-1}$, respectively). At Casa Branca, yields increased from 31.5 $t \cdot ha^{-1}$ for the control to 42.4 $kg \cdot ha^{-1}$ at the 62 kg K/ha application rate with no further increases at higher rates and no differences among fertilizer blends at any application rate. Polyhalite blend increased dry matter and starch at the higher application rates compared with MOP and SOP at Tapira and increased potato hardness and crunchiness at the optimum 62 kg K/ha application rate at Casa Branca. Yield response was similar for PH and SOP but quality differences between these two fertilizer blends were observed even though they were similar in composition. Differences between PH and MOP may be related either to Cl or lack of Mg in the MOP blend. PH performed well as a fertilizer for potatoes as it produced equal or higher yields and provided benefits to potato quality when compared with MOP or SOP as a K source in a common fertilizer blend.**

Polyhalite is a naturally occurring potassium, calcium, magnesium sulfate mineral with a chemical formula $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$ corresponding to 13.0% K, 13.3% Ca, 4.0% Mg, and 21.3% S. Many horticultural crops including potatoes (*Solanum tuberosum* L.) require each of the nutrients in PH, often in significant quantities, and are commonly included in nutrient management programs. Polyhalite has a known potential as a fertilizer (Barbarick, 1989; Fraps, 1932) but has had limited use worldwide because it has not been commercially available. Consequently, literature on the performance of PH fertilizer for agronomic crops is very limited compared with common commercial fertilizer sources used to supply K, Ca, Mg, and S to plants. With the discovery of the largest high-grade known resource of PH in the world, the Zechstein deposit located in the southern North Sea Basin in the United Kingdom (Kemp et al., 2016), PH fertilizer is becoming available worldwide. Polyhalite fertilizers from the Zechstein deposit have purities approaching 90% and have a guaranteed analysis of 12% of K, 12% Ca, 3.6% Mg, and 19% S (Sirius Minerals, 2016). Polyhalite is a neutral salt with a solubility of 27 $g \cdot L^{-1}$ at 25 °C, lower than potassium chloride and potassium sulfate, and has <3% Cl, making it suitable for chloride-sensitive crops such as potatoes.

Potatoes make an ideal crop to evaluate PH as a fertilizer. Westermann (2005) reported K uptake in potatoes to exceed N, P, Ca and Mg with an average uptake of 4.2 kg of N, 0.55 kg of P, 6.0 kg of K, 1.6 kg of Ca, 1.1 kg of Mg, and 0.4 kg of S per ton of tuber yield. In addition, chloride or salt content can negatively affect dry matter percentage (Panique et al., 1997; Roy et al., 2017) and petiole nitrate contents (James et al., 1994) such that nonchloride forms of K are desired as potato fertilizers. Because potatoes are commercially grown on soils often inherently low in fertility and irrigated to achieve high yields and tuber quality, large quantities of fertilizers, particularly N, P, and K, are frequently applied.

Potassium influences both quantity and quality of potatoes (Karam et al., 2011; Lakshmi et al., 2012) through various mechanisms such as enzyme activation (Werij et al., 2007), stomatal conductance, photosynthesis, protein synthesis, and transport of sugars and starch (Mengel and Kirkby, 1987). Potassium application resulted in higher leaf area, increased plant height, prolonged bulking duration, enhanced tuber size, and a higher proportion of medium and large size grades and higher yields (Trehan et al., 2001). Potassium also affects dry matter percentage, increases ascorbic acid content, decreases reducing sugars, phenol contents, and enzymatic degradation (Werij et al., 2007). Calcium is important for potato growth, development, and yield (Chang et al., 2007; Kumar et al., 2007a). Calcium influences tuber grade index, dry matter content, and tuber quality (Tawfik 2001); and improves cell wall rigidity, firmness, plasma membrane structural stability, and tuber periderm calcium concentrations. Thus, plant resistance to diseases and tuber disorders such as brown center, hollow heart, internal brown spot, black leg, gangrene (Kondo et al., 2001), and soft rot (Abo-Elyousr et al., 2010) are affected by Ca nutrition. Magnesium is a constituent of chlorophyll molecules and affects photosynthesis (Peaslee and Moss, 1966), carbon allocation, and the level of reactive oxygen species at molecular levels (Cakmak and Kirkby, 2008). At the canopy level, Mg increases N, P, and K uptake and thereby, increases yield (Kene et al., 1990). Sulfur plays a significant role in amino acid, protein, and chlorophyll synthesis and influences N metabolism and tuber composition by decreasing sugar content (Muttucumaru et al., 2013) and by controlling diseases such as common scab and black scurf.

Potato is the fourth most important crop in the world with a total production of ∼374 million tons consumed by more than 1 billion people (CIP-International Potato Centre, 2014). An increasingly important crop in Brazil, 3.7 million tons are produced on 0.13 million ha with an average yield of 28 $t \cdot ha^{-1}$ (FAO–Food and Agriculture Organization, 2017). Potato production in Brazil is concentrated in the Southeast in two states where the soil and climate are most conducive to potato production; São Paulo and Minas Gerais produce more than 50% of the nation's total potato crop with an average yield of 30 $t \cdot ha^{-1}$ (IBGE, 2017). Mean potato yield in Brazil is lower than in the United States where potato yields in 2015 averaged 47 $t \cdot ha^{-1}$ with a high of 68 $t \cdot ha^{-1}$ in Washington State (USDA, 2016), reflecting more difficult growing conditions in the humid subtropical climate. Because the soils in Brazil are deep and highly weathered, and frequently deficient in many plant nutrients (Bernardi et al., 2002), they may respond to the nutrients in PH fertilizer.

Fertilization rate for potatoes in Brazil is high with an average K application rate of 189 $kg \cdot ha^{-1}$ reported by Bernardi et al. (2002) and 166 $kg \cdot ha^{-1}$ reported by IBGE (2017) but varies considerably: 199–374 kg K/ha, 64–250 kg N/ha, and 196–371 kg P/ha (Schepers et al., 2015). Fertilizers are predominately applied in blends, such as 4–14–8, in which triple super phosphate (TSP) or SSP is used as the P source such that Ca, and S in the case of SSP, is provided in the blend. Additional N is applied at hilling, and ammonium sulfate (AS) is a common N source which provides S. Of interest is that there is a shift occurring in Brazil to lower costs by shifting to urea as the N source and MAP as the P source which would eliminate Ca and S in the blends. Bernardi et al. (2002) reported the N, P, K, Ca, Mg, and S removed per metric ton of tuber yield in Brazil to be 3.0, 0.3, 4.0, 0.2, 0.2, and 0.2 $kg \cdot ha^{-1}$, respectively, considerably less than that reported by Westermann (2005) for potatoes grown in the United States where yields are higher.

The response of potato crop to MOP or SOP depends on the soil fertility, climate, and crop variety grown (Bansal and Kumar, 1998). The effects of K in a fertilizer are associated with the way in which it is chemically combined in the fertilizer (Zehler et al., 1981). The accompanying anion may affect the uptake of nutrients, yield, and quality of potato. For example, Pavuluri et al. (2017) indicated the role of sulfur in PH in increasing corn (*Zea mays* L.) grain yields compared with MOP in the southern highland region of Tanzania. Similarly, enhanced yield from PH compared with MOP, SOP, and magnesium potassium sulfate (SOPM) was attributed to Ca by Mello et al. (2018) in tomato (*Solanum lycopersicum* L.) in the São Paulo region of Brazil under very low soil K conditions. In soils with S deficiency, SOP has been more effective in increased yield of potato than MOP (Bansal, 2003). However, studies also showed that MOP was similar or higher than SOP for potato quantity and quality, and yield (Davenport and Bentley, 2001; Khan et al., 2010, 2012; Panique et al., 1997). Lower solubility of PH relative to MOP or SOP could be advantageous for plant nutrient uptake in the tropical conditions of Brazil by reducing the leaching loss of nutrients and by improving the residual effect of fertilizers on subsequently grown crops (Yermiyahu et al., 2017).

We investigated how a common fertilizer blend in Brazil made with MOP as the K source and SSP as the P source compared with the same blend made with either PH or a synthetic PH created using a mixture of SOP, kieserite, and gypsum with MAP as the P source for commercial potato production. Our main interest in this paper is whether the three blends perform similarly with respect to tuber yield and quality in two different growing environments in the dry season and the wet season.

Materials and Methods

Field experiments were conducted in commercial potato fields in two locations in Southeast Brazil at Tapira, Minas Gerais State (lat. 19°55′S and long. 46°49′W, elevation 1091 m) in the Sept. 2015 to Jan. 2016 growing season (wet season) and at Casa Branca, São Paulo State (lat. 21°46′S and long. 47°05′W, elevation 1091 m) in the July to Nov. 2016 growing season (winter season). The soils are deep, well drained, and naturally low in fertility such that they are generally responsive to fertilizers. The soil at Tapira has a sandy surface texture and the soil at Casa Branca has loamy sand surface texture. Composite soil samples were collected at both locations from the 0 to 20 cm depth from each plot with a 2.5 cm diameter soil auger both prior planting and post-harvesting. The composite samples were mixed, air dried, sieved with a 2-mm mesh sieve and subsamples analyzed for pH ($CaCl_2$ 0.01 $mol \cdot L^{-1}$), and electrical conductivity of saturated soil-paste using conductivity meter bridge as per the methods described by Richard (1954). Ion exchange resin extraction procedure was used to measure P, K, Ca, and Mg (van Raij et al., 1986), SO_4-S [Ca $(H_2PO_4)_2$ 0.01 $mol \cdot L^{-1}$] using standard procedures (van Raij et al., 2001). The average soil K at Tapira was medium, i.e., 86 $mg \cdot kg^{-1}$, and the recommended K fertilizer rate for potato at this site was 125 kg K/ha (van Raij et al., 1997). At Casa Branca, the soil K was low, i.e., 43 $mg \cdot kg^{-1}$, according to the soil analysis interpretation guide of São Paulo State (van Raij et al., 1997). The recommended K fertilizer rate for potato at Casa Branca was 208 kg K/ha. Soil Ca and Mg concentrations at Tapira were high and medium, i.e., 562 mg Ca/kg and 106 mg Mg/kg, and at Casa Branca were high and low, i.e., 293 mg Ca/kg and 89 mg Mg/kg. The soil S concentrations were high (40 $mg \cdot kg^{-1}$) at Tapira and low (4 $mg \cdot kg^{-1}$) at Casa Branca (van Raij et al.,1997). There is no recommended soil test for S, and therefore, no soil test–based S recommendation for potatoes in Brazil. Air temperature and precipitation were measured at 30-min intervals from planting to harvest using weather stations WatchDog WD 2700, (Spectrum Technologies, Inc., Aurora, IL) installed at 1.5 m of height at each experimental site.

Treatments and experimental design. Commercially, fertilizers for potato production are applied in blends commonly made with AS or urea as the N source, SSP and/or TSP as the P source, and MOP as the K source such that the final NPK blend contains significant amounts of Ca and S. To evaluate PH as a fertilizer for potatoes, we compared a common NPK fertilizer blend (4–14–8) used for potato production in Southeast Brazil made as done commercially with urea, TSP, and MOP with PH and a synthetic version of PH made with SOP, kieserite ($MgSO_4 \cdot H_2O$), and gypsum ($CaSO_4 \cdot 2H_2O$) added in quantities to match the Ca, Mg, and S in PH. Fertilizer was applied at four K application rates (62, 124, 187, and 249 kg K/ha) with constant N and P applied at 150 and 229 $kg \cdot ha^{-1}$ according to the local recommendations. A treatment with N and P but no K, Ca, Mg, or S applied was included as a control. The experimental design was a 3×4 factorial plus single control treatment structure arranged in randomized complete block design. All fertilizer treatments were replicated four times with the control replicated three times in each block for a total of 12 replicates of the control. The N fertilizer source for all blends was urea, but the P fertilizer source varied with the blend, with SSP in the MOP based blend and MAP in the PH and SOP based blends and in the control. To achieve the four K application rates in a blended fertilizer, the K content of the blend was varied from 2% to 8% for each K source. Thus, the Ca, Mg, and S varied with K rate in the PH and SOP based blends, from 64 to 129 kg Ca/ha and 105 to 424 kg S/ha, but given the constant P application rate, the SSP provided Ca and S at a constant rate in the MOP blend, 574 and 326 $kg \cdot ha^{-1}$, respectively, but no Mg (Table 1). All Ca and S application rates would have exceeded recommendations based on plant removal of these nutrients at the two sites. We applied all fertilizer treatments as blends before planting in a band directly under the row and covered it so that the seed piece would be planted 15 cm above the fertilizer band. At Tapira, boron was

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Table 1. Nutrients applied at the time of planting for each K application rate.

	K	N	P	Ca	Mg	S	Cl
Treatment	kg·ha^{-1}						
Control	0	150	229	0	0	0	0
MOP	62	150	229	574	0	326	60
	124	150	229	574	0	326	120
	187	150	229	574	0	326	180
	249	150	229	574	0	326	240
SOP	62	149	229	64	19	105	0
	124	149	229	131	38	214	0
	187	149	229	195	60	319	0
	249	149	229	259	79	424	0
PH	62	149	229	64	19	101	16
	124	149	229	131	38	203	32
	187	149	229	195	60	304	48
	249	149	229	259	79	409	64

MOP = muriate of potash; SOP = sulfate of potash; PH = polyhalite.

applied as granules at a rate of 4 kg B/ha along with the previous fertilizer blends. At about 30 d after planting, additional N fertilizer was applied as ammonium nitrate at a rate of 80 kg N/ha at Tapira whereas at Casa Branca the grower applied AS rather than urea at a rate of 126 kg N/ha which applied an additional 30 kg S/ha to all treatments that is not included in Table 1.

Each plot consisted of four rows of potato spaced 0.8 m apart, with 0.35 and 0.30 cm spacing between plants at Tapira and Casa Branca, respectively, corresponding to plant populations of 35,714 and 41,667 plants/ha, respectively. Plots at Tapira had 100 plants per row and at Casa Branca 15 plants per row, corresponding to experimental plot sizes of 112 and 14 m^2, respectively.

Agronomy. Potatoes (cultivar Asterix, a red tuber with yellow flesh used for French fries and processed products) were planted on 4 Sept. 2015 at Tapira and at Casa Branca (cultivar Romeo, a red skin white flesh potato for fresh market and for chips) on 28 July 2016. Tillage at both locations included plowing and harrowing before potato fertilization and planting. The irrigation was through center pivots twice a week at application rates sufficient for soil moisture to attain field capacity. The management practices to control insects and diseases were as per recommendations by Kimati et al. (1997) and Gallo et al. (2002). Plants emerged at Tapira on 19 Sept. 2015 and at Casa Branca on 12 Aug. 2016. Potatoes were hilled and N fertilizer applied at Tapira on 28 Sept. 2015 and at Casa Branca on 23 Aug. 2016.

We harvested potatoes at Tapira on 16 Jan. 2016, 135 d after transplanting (DAT) from 30 plants from the center two rows and at Casa Branca on 5 Nov. 2016, 101 DAT from a 3 m length of the center two rows. We determined the number of tubers, total yield, marketable yield and nonmarketable yield. Tubers were graded according to the transverse diameter into categories: <28 mm (very small), 28–33 mm (small), 33–42 mm (medium), 42–70 mm (large), and >70 mm (very large), with the first four used at Tapira and the last four used at Casa Branca. Marketable yield was calculated as the sum of the tuber weight of the previously mentioned four categories. Nonmarketable tubers manifested physiological disorders and/or insects and disease infestation symptoms. The total yield was calculated as the sum of marketable and nonmarketable yields.

Postharvest quality evaluations. Dry matter percentage, total soluble solids, nutrient concentrations, and starch content (%) were evaluated from five tuber samples from each plot. Tubers were dried at 68 °C until they reached a constant weight and from the dry weight/wet weight we calculated dry matter percentage. Tubers were rinsed with deionized and distilled water and were peeled and cut. They were dried in a glass petri dish and ground with a ball mill (MM200; Retsch GmbH) with a 1 mm screen. The dried tubers were ground and a subsample analyzed for N, P, K, Ca, and Mg according to Malavolta et al. (1997). We determined total soluble solids from two drops of the juice obtained by macerating slices of the potato pulp that were placed in the prism of the electronic refractometer. Tuber starch content was determined as described by Rickard and Behn (1987) with readings made using a spectrophotometer at 535 nm, reported on a fresh weight basis.

We determined potato hardness and crunchiness in a texturometer (TAXTplus Texture Analyzer; Stable Micro Systems LTD., Godalming, UK) under the following conditions: force measurement in compression, pretest and test speeds of 3.0 mm·s^{-1}, a posttest speed of 10.0 mm·s^{-1}, and a distance of 30.0 mm. Potato hardness was determined by measuring the maximum force (N) required to cut each toothpick in the transverse direction, central region. The higher the peak of the force vs. distance curve obtained during the analysis, the greater the hardness. We measured potato crunchiness, characterized by the resistance to deformation at the time of sample cutting, in N/mm from the slope of the force vs. distance curve, with increasing crunchiness with increasing slope (Sham et al., 2001).

Statistical analysis. We analyzed each location as 3 × 4 factorial + single-control design described by Piepho et al. (2006) using the factorial plus added control structure procedures in the GENSTAT statistical analysis software (Payne, 2009). As presented by Payne (2009), this structure allows the comparison of any fertilizer at any (nonzero) application rate to the control treatment, the comparison between application rates averaged over the different fertilizer sources, comparison of overall differences between fertilizer sources averaged over application rates, and the interaction between application rate and fertilizer source given that some sort of fertilizer has been applied. Because of the differences in growing seasons between the two sites and significant interactions of site and treatments, variables were analyzed by site as was performed by Zhu et al. (2017) and Pavuluri et al. (2014). We used Fisher's LSD at the 10% significance level to compare means when F tests indicated that significant differences existed ($P < 0.05$–0.1). We fit a variable's response to K application rate for each fertilizer source using linear, quadratic, and exponential models when ANOVA *P* values were significant. Models were selected based on higher r^2 and significance (*P* values).

Results and Discussion

Our expectations were that potato yield and quality would increase with increasing K application rate. We expected that the SOP and PH blends would have similar effects on potatoes given that the SOP was essentially a synthetic version of PH, although any differences between them could be associated with the lower solubility of PH than SOP and kieserite (27 vs. 120 and 417 g·L^{-1} at 25 °C, respectively) and possibly gypsum in the SOP blend (2 g·L^{-1} at 25 °C) such that K and Mg could be available quicker and Ca slower from the SOP blend than PH. We expect differences between the MOP and the SOP and PH blends to be associated with the Cl in MOP and the lack of Mg in the MOP blend. Because Ca and S are provided in all fertilizer blends, no response to these nutrients was expected except in the control treatment which received only N and P fertilizers.

Total and Marketable Yields. Average tuber yield over all treatments at Tapira was 27 t·ha^{-1} compared with 40 t·ha^{-1} at Casa Branca. The major difference in yield is likely related to the growing season differences, with the Tapira study conducted during the wet season and the Casa Branca study conducted during the winter season which is known to have higher productivity and better quality under irrigation and less bacteria and late blight (*Phytophthora infestans* L.) than in the wet season (Schepers et al., 2015). During the study periods, mean daily maximum and minimum temperatures were similar at both locations, 28.1 and 14.1 °C at Tapira and 28.3 and 14.5 °C at Casa Branca, respectively. However, total seasonal precipitation was three times higher at Tapira than at Casa Branca, 660 and 206 mm, respectively.

For all but the very small (<28 mm) tuber size category at Tapira, for which there was no consistent trend, there were no significant interactions between fertilizer source and application rate at either location (Table 2). Therefore, only the main effects of fertilizer source and application rate, and their comparison with the control is relevant with respect to tuber yield. The control treatment produced less total tuber yield than the average of the fertilizer treatments at both locations, 26% less at Tapira and 35% less at Casa Branca (Tables 2 and 3).

At Tapira, there was a linear response of total yield to fertilizer rate for all fertilizer blends, indicating that the highest fertilizer application rate may not have been sufficient (Fig. 1). The SOP and PH treatments produced higher total tuber yields than the MOP treatment, 15.4% and 11.4%, respectively (Table 2), indicating that the MOP treatment reduced tuber production but had a similar linear response to application rate. At Casa

Table 2. *P* values from analysis of variance (ANOVA) and least square means of yield in response to different K sources and rates at Tapira, Brazil, in 2015.

	Yield ($t \cdot ha^{-1}$)							
Variable	Total	Marketable	Nonmarketable	Very small[z]	Small	Medium	Large	Very large
Source								
Control	22.4 a[y]	16.3 a	6.1 c	—[x]	2.0	6.4 a	7.5 a	0
MOP	25.3 b	22.2 b	3.0 a	—	2.2	9.8 bc	9.8 b	0
SOP	29.2 c	24.9 c	4.3 b	—	2.3	10.7 c	11.3 c	0
PH	28.8 c	24.0 bc	4.8 b	—	2.7	8.7 b	12.2 c	0
Rate (kg K/ha)								
0	22.4 a	16.3 a	6.1 c	—	2.0 a	6.4 a	7.5 a	0
62	24.6 ab	19.4 b	5.2 bc	—	1.8 a	8.0 b	9.0 ab	0
124	27 bc	22.3 c	4.7 b	—	2.4 ab	9.9 c	9.6 b	0
187	28.4 cd	26.1 d	2.3 a	—	2.4 ab	10.5 c	12.7 c	0
249	31.0 d	27.1 d	3.9 b	—	3.0 b	10.5 c	13.2 c	0
Control vs. Noncontrol[w]	<0.001	<0.001	0.003	0.071	NS	<0.001	<0.001	ND
Control × K source	0.018	0.081	0.051	NS	NS	0.029	0.036	ND
Control × K rate	0.004	<0.001	0.008	NS	0.064	0.01	<0.001	ND
Control × K source × K rate	NS	NS	NS	0.018	NS	NS	NS	ND

[z]Tubers were graded according to the transverse diameter into categories: <28 mm (very small), 28–33 mm (small), 33–42 mm (medium), 42–70 mm (large), and >70 mm (very large).
[y]Means within type and rate of K sources followed by the same letter are not significantly different ($P > 0.1$).
[x]Data were not presented for the variable because of significant interaction between K blends and rates of K in ANOVA.
[w]Noncontrol indicates a combination of different K sources and nonzero rates.
NS = nonsignificant; ND = not determined; MOP = muriate of potash; SOP = sulfate of potash; PH = polyhalite.

Table 3. *P* values from analysis of variance (ANOVA) and least square means of yield in response to different K sources and rates at Casa Branca, Brazil, in 2015.

	Yield ($t \cdot ha^{-1}$)							
Variable	Total	Marketable	Non-marketable	Very small[z]	Small	Medium	Large	Very large
Source								
Control	31.5 a[y]	29.8 a	1.7	0	12.7	12.7 a	4.1 a	0.4
MOP	43.5 b	41.8 b	1.7	0	15.1	17 b	8.7 b	1.0
SOP	42.3 b	40.7 b	1.5	0	15.0	16 b	8.8 b	1.0
PH	41.5 b	39.6 b	1.9	0	13.8	17 b	8.1 b	0.6
Rate (kg K/ha)								
0	31.5 a	29.8 a	1.7	0	12.7	12.7 a	4.1 a	0.4
62	43.9 c	42.5 c	1.4	0	15.4	17.0 b	9.9 b	0.3
124	43.9 c	41.5 c	2.4	0	14.2	19.0 b	7.4 b	0.9
187	43.8 c	42.4 c	1.3	0	15.7	15.9 b	9.6 b	1.3
249	38 b	36.3 b	1.7	0	13.4	14.7 b	7.2 b	1.1
Control vs. Noncontrol[x]	<0.001	<0.001	NS	ND	NS	0.025	<0.001	NS
Control × K source	NS	NS	NS	ND	NS	NS	NS	NS
Control × K rate	0.009	0.012	NS	ND	NS	NS	NS	NS
Control × K source × K rate	NS	NS	NS	ND	NS	NS	NS	NS

[z]Tubers were graded according to the transverse diameter into categories: < 28 mm (very small), 28–33 mm (small), 33–42 mm (medium), 42–70 mm (large), and >70 mm (very large).
[y]Means within type and rate of K sources followed by the same letter are not significantly different ($P > 0.1$).
[x]Noncontrol indicates a combination of different K sources and nonzero rates.
NS = nonsignificant; ND = not determined; MOP = muriate of potash; SOP = sulfate of potash; PH = polyhalite.

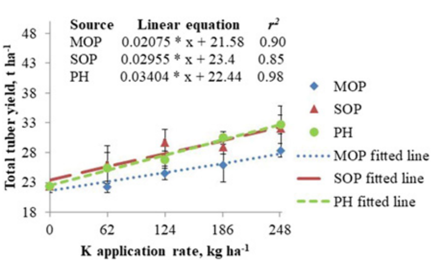

Fig. 1. Total potato yield response to fertilizer type and potassium (K) application rates at Tapira, Brazil. Error bars indicate standard error of the means. MOP = muriate of potash; SOP = sulfate of potash; PH = polyhalite.

Branca, total yield increased 40% from the control to the 62 kg K/ha with no additional changes at the 124 and 186 kg K/ha rates but a decline of 16% at the 248 kg K/ha (Table 3). Hence, the optimum rate for tuber yield at Casa Branca was 62 kg K/ha, irrespective of fertilizer source. Marketable yield response to fertilizer rate mimicked total yield and was lower in the control than all fertilizer blends at both locations (Tables 2 and 3). No differences in marketable yield because of fertilizer type was observed at Casa Branca, but at Tapira, marketable yields were 11.2% higher for SOP than MOP with PH not different among fertilizer sources. Very small potato yields at Tapira were higher than the control at the 187 and 249 kg K/ha application rates in the PH and the 124 and 249 kg K/ha in the SOP treatments which were similar, indicating that higher application rates of SOP and PH increased tubers in this size category. Given that total yield response to fertilizer application rate was linear and total yields higher in the SOP and PH treatment, additional fertilizer applications may have increased yields in these two treatments more than in the MOP treatment. Small potatoes were unaffected by fertilizer type or application rate at Casa Branca but increased with application rate at Tapira, from 2 $t \cdot ha^{-1}$ in the control to 3 $t \cdot ha^{-1}$ at the 249 kg K/ha application rates regardless of fertilizer type. Similarly, medium potatoes increased with application rate at Tapira, from 6.4 $t \cdot ha^{-1}$ in the control to 10.5 $t \cdot ha^{-1}$ at the 187 and 249 kg K/ha application rates regardless of fertilizer type. Yields of medium and large potatoes mimicked total and marketable yields with yields of control less than fertilizer-applied yields at both locations. At Tapira, yields of medium potatoes were 22.0% lower in PH than in SOP with MOP intermediate whereas large potatoes were 24.5% and 15.3% higher in PH and SOP than in MOP, respectively (Table 2). Yields of very large potatoes at Casa Branca were low and unaffected by fertilizer type or application rate (Table 3). Nonmarketable yields were low at Casa Branca and unaffected by fertilizer type or rate whereas nonmarketable potato yields declined at Tapira with increasing K application rate, from 27.4% for the control to a low of

8.3% for the 200 kg K/ha application rate. MOP had the lowest nonmarketable potato yields, 0.5% of total yield, and the control the highest with SOP and PH intermediate (14.7% and 16.7%, respectively), which reflects higher total yields in those treatments than in MOP.

In spite of lower soil test levels for K, Ca, Mg, and S at Casa Branca than at Tapira, more favorable growing conditions in the winter season than the wet season proved more important to potato yield than soil fertility. The response at the two sites were markedly different, linear at Tapira and no response to rate increases from 62 to 187 kg K/ha at Casa Branca, suggesting different fertilizer needs for the two sites.

Lower total tuber yields in the MOP treatment at Tapira may be associated with either Cl contents, lack of Mg, or both. Although not conclusive among studies, Maier (1986) reported that MOP at planting significantly reduced fresh tuber yield compared with SOP at 2 of 14 tested sites in South Australia at 133 kg K/ha. Panique et al. (1997) reported that SOP application tended to enhance yields more than MOP at rates up to 280 kg K/ha in Wisconsin, USA. Magnesium is the central atom of the chlorophyll molecule, therefore essential for photosynthesis, enhancing the productivity of crops such as potato (Cakmak and Yazici, 2010). In addition, yield response to Mg could also be attributed to the alleviation of Al toxicity in acidic and weathered soil conditions by catalyzing the release of organic acid anions from roots, which in turn chelate toxic Al cations (Ferdous et al., 2014; Cakmak and Yazici, 2010). The addition of kieserite to the MOP blend would resolve the role of Mg deficiency in the lower yields of this blend at Tapira. Potassium influence on enhancing the proportion of medium and large size potatoes was widely established (Al-Moshileh et al., 2005; El-Latif et al., 2011; Perrenoud, 1993). This could be because of improved bulking rate and persistence and continuation of late season crop growth.

Tuber Quality. The quality of potato tubers is a complex trait that depends on its intended usage. Cultivar Asterix at Tapira is mainly used for frying and chip-making purposes for the processing industry. High dry matter and starch content improve texture, and low reducing sugar contents result in less darkening of fries which is desirable. High dry matter percentage enables lower oil absorption while frying, resulting in lower oil usage per unit product. Tuber firmness is essential to handle mechanical stresses that may occur during tuber harvesting, transport, and storage. Crunchiness and hardness are positively related to starch and dry matter contents and specific gravity.

At Tapira, there was a significant interaction between K source and application rate for dry matter, starch, and total soluble solids. Tuber dry matter percentage was higher than the control (15.1%) and similar among fertilizer sources (average 16.2%) for the 62 and 125 kg K/ha application rates (Fig. 2). Tuber dry matter increased with an increasing application rate for PH but was asymptotic after an increase greater than the control at the 62 kg K/ha application rate for MOP and SOP (Fig. 2). The influence of source and rate of K fertilizer on tuber dry matter content has been widely investigated (Maier et al., 1986; Panique et al., 1997; Ramona and Tomasiewicz, 2012). Kumar et al. (2007b), and Manolov et al. (2016) reported enhanced dry matter percentage by the application of SOP compared with MOP. Potassium influence on dry matter percentage is complex and dynamic. Both K and Mg enhance the synthesis of carbohydrates and their translocation from leaves into tubers by assisting in phloem loading (Mengel and Kirkby, 1987). Potassium could improve dry matter percentage and starch content by stimulating starch synthase enzyme and K helps in the incorporation of glucose into long-chain starch molecules (Mengel and Kirkby, 1987). Despite improved starch synthesis and translocation, K could reduce overall dry matter percentage by increasing water content in tubers (Perrenoud, 1993). The latter scenario is particularly true at luxury K consumption by crop. Perrenoud (1993) also observed decreased dry matter percentages due to chloride anions from MOP compared with SOP. The reasons for high dry matter percentage in PH are not clear and may not be attributed to Mg content as both SOP and PH blends contain similar amounts of Mg. Further evidence is needed to confirm and understand these observations. Tuber starch content was higher in all fertilizer K sources and rates (10.9% to 14.3%) than in the control (9.9%) and increased linearly with increasing K application rate for PH and SOP (Fig. 2). For MOP, the tuber starch rate response was asymptotic after an increase greater than the control at the 62 kg K/ha application rate (Fig. 2). For PH, starch dropped from 12.3% to 10.9% starch from the 62 to the 125 kg K/ha application rate and then increased linearly with K application rate to a high of 14.3% starch. SOP mimicked the PH pattern for starch response to K application rate. Starch and dry matter contents are generally positively correlated (Gerendás and Führs, 2013). Reasons for different dry matter percentages between SOP and PH but similar starch contents at 186 and 249 $kg \cdot ha^{-1}$ K_2O rates were not clear. Manolov et al. (2016) reported higher starch content from SOP compared with MOP with equal rates of K in both greenhouse pot experiments and field studies. There was no effect of K application rate on hardness or crunchiness but PH had higher hardness, 15.8 N compared with a range of 13.5–14.4 N, and crunchiness (1.42 compared with 1.2 N/mm)

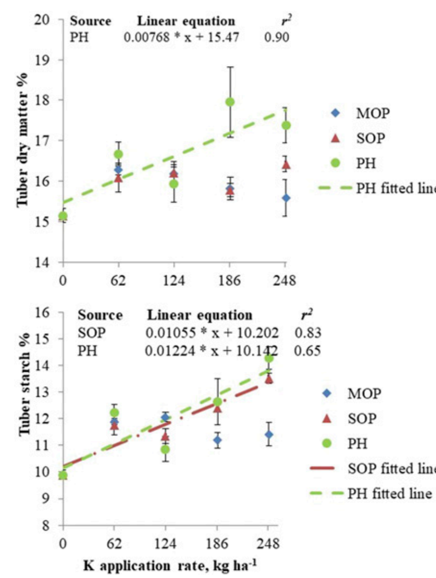

Fig. 2. Dry matter content and starch in potatoes for three fertilizer sources over a range of potassium (K) fertilizer application rates at Tapira, Brazil. Error bars indicate standard error of the means. MOP = muriate of potash; SOP = sulfate of potash; PH = polyhalite.

Table 4. *P* values from analysis of variance (ANOVA) and least square means of tuber quality parameters in response to different K sources and rates at Tapira and Casa Branca, Brazil, in 2015–16.

	Location			
	Tapira		Casa Branca	
Variable	Hardness (N)	Crunchiness (N/mm)	Dry matter (%)	Starch (%)
Source				
Control	13.5 a[z]	1.2 a	17.5	12.5
MOP	13.5 a	1.2 a	17.5	12.1
SOP	14.4 a	1.2 a	18.7	13.0
PH	15.8 b	1.4 b	18.5	12.7
Rate (kg K/ha)				
0	13.5 a	1.2	17.5	12.5
62	14.8 b	1.3	18.0	12.6
124	15.1 b	1.3	18.0	12.5
187	13.7 b	1.2	17.9	12.3
249	14.8 b	1.3	18.8	13.0
Control vs. Noncontrol[y]	0.029	NS	NS	NS
Control × K source	<0.001	0.002	NS	NS
Control × K rate	NS	NS	NS	NS
Control × K source × K rate	NS	NS	NS	NS

[z]Means within type and rate of K sources followed by the same letter are not significantly different ($P > 0.1$).

[y]Noncontrol indicates a combination of different K sources and nonzero rates.

NS = nonsignificant; ND = not determined; MOP = muriate of potash; SOP = sulfate of potash; PH = polyhalite.

for the other fertilizer sources and control (Table 4). Tuber hardness ranged from 13.5 to 15.8 N, higher than 9.31 N hardness reported by Fernandes et al. (2010) for cultivar, Asterix. Total soluble solids for the MOP treatment (3.9% to 4.2%) were not different from the control (4.1%) for all K application rates but the trend was for it to decline with increasing application rate (Fig. 3). SOP had the highest total soluble solids (4.3% to 4.4%) at all but the 125 kg K/ha application rate, which was similar to the control. PH had the lowest total soluble solids (3.7%) at the 62 kg K/ha application rate but similar values to that of MOP at higher application rates. Total soluble solids at higher application rates were not different from the control.

At Casa Branca, there was a significant interaction between fertilizer source and application rate for total soluble solids (Fig. 3), hardness, and crunchiness (data not shown) but no effect of fertilizer source or application rate on dry matter percentage or starch content (Table 4). Dry matter averaged 17.5% similar to the 17.4% observed for the PH high-application rate treatments at Tapira (Fig. 2) and starch averaged 12.6% overall comparable to the fertilizer average of 12.1% at Tapira but less than the 14.3% starch in the 249 kg K/ha application rate for PH at Tapira. Total soluble solids were higher at Casa Branca than at Tapira, 5.0% vs. 4.1%, respectively, for the control. Total soluble solids increased with MOP at all but the highest K application rate, decreasing to 4.8% at the 249 kg K/ha application rate (Fig. 3). The SOP 62 kg K/ha application rate increased total soluble solids but, they declined with increasing K application rate, with a low of 4.8% at the 187 kg K/ha rate (Fig. 3). PH decreased total soluble solids at the 62 kg K/ha application rate to 4.8% but total soluble solids increased with increasing application rate to a high of 5.2% at the 249 kg K/ha

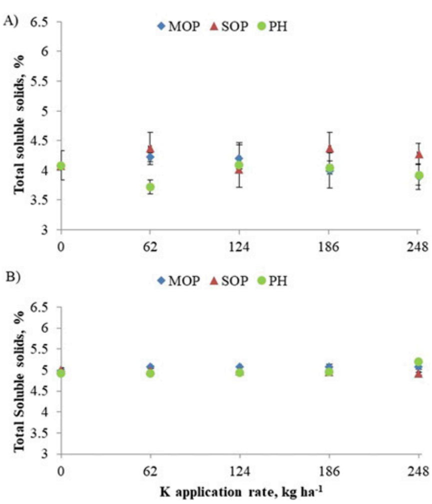

Fig. 3. Total soluble solids in potatoes for three fertilizer sources over a range of potassium (K) fertilizer application rates at (**A**) Tapira and at (**B**) Casa Branca in Brazil. Error bars indicate standard error of the means. K = potassium; MOP = muriate of potash; SOP = sulfate of potash; PH = polyhalite.

application rate (Fig. 3). Total soluble solids at Casa Branca are comparable to the numbers reported by Feltran et al. (2004) for various genotypes, ranging from 3.9% to 6.9% in São Paulo, Brazil.

Potato hardness at Casa Branca was unaffected by MOP at any application rate averaging 18.5 N compared with 18.8 N for the control, but was higher in the PH and SOP treatments than in the control and MOP at the 62 kg K/ha application rate (20.9 and 21.2 N, respectively) and for SOP at the 187 kg K/ha application rate, i.e., 21.3 N. There was no effect of any fertilizer at the 249 kg K/ha application rate. Crunchiness was highly correlated to hardness such that the response of crunchiness to fertilizer type and application rate was similar. Crunchiness was unaffected by MOP at any application rate but was higher for PH and SOP at the 62 kg K/ha application rate and for SOP at the 187 kg K/ha application rate but lower than the control for PH at the 187 kg K/ha application rate.

The optimum K application rate at Casa Branca for total tuber and marketable yield was 62 kg K/ha, the rate at which hardness and crunchiness were highest and total soluble solids lowest for PH than that for MOP. At that application rate, the SOP had higher soluble solids compared with PH but similar hardness and crunchiness. Therefore, although tuber yields were unaffected by fertilizer source, when applied at the optimum response rate, PH improved tuber quality compared with MOP and SOP. At higher K application rates, the relative response to these quality parameters varied by fertilizer source. For PH, hardness and to a minor extent crispiness declined, but total soluble solids increased with increasing K application rates. Potato growers in Brazil apply high rates of K often exceeding rates used at Casa Branca. At the highest application rate used in this study, total soluble solids would be higher in the PH treatment and there would be no effect of fertilizer type on hardness and crunchiness. Clearly, the addition of excess fertilizer had an impact on potato quality but not yield at Casa Branca. The variable and often negative response of potato quality to higher fertilizer rates for the different K sources is not clear given that the fertilizers were similar in K, Ca, and S contents with only Cl and Mg contents differing.

Polyhalite based fertilizer blends, including a synthetic version of PH (SOP), increased total and marketable potato yields by 14% to 15% compared with MOP based blends at Tapira, São Paulo, grown in the wet season where excess rainfall creates adverse conditions that reduce yield potential and potato quality. Because yield response to fertilizer application rate was linear, we believe that additional fertilizer applications could have further increased yields. We suspect that excess Cl and or lack of Mg in the MOP blend have contributed to the yield differences observed at this location. PH increased potato quality by increasing dry matter by 13% and starch 25% compared with MOP at the higher fertilizer application rates.

Tuber yields were higher at Casa Branca because of lower rainfall in winter than at Tapira. Maximum yield at Casa Branca was observed at the 62 kg K/ha application rate with increased yields of 32% to 40% regardless of fertilizer blend. Although PH did not affect potato yields differently than the other blends, potato hardness and crunchiness were higher with PH than the other blends at the low fertilizer application rate. At both locations, soluble solids were lower in PH at the 62 kg K/ha rate but increased with increasing application rate to levels similar to or higher than MOP at the higher application rates. Yield response was similar at both locations for PH and SOP but some differences were observed in potato quality suggesting that a synthetic version of PH affects potato differently than natural PH, although the reason for the differences are not clear from this study. Polyhalite performed well as a fertilizer for potatoes as it produced equal or higher yields and provided benefits to potato quality when compared with MOP or SOP as a K source in a common fertilizer blend in Brazil.

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