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Polyhalite as a sulfur source for fresh market tomato production in Brazil

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ABSTRACT

Polyhalite (PH), a naturally occurring multinutrient fertilizer containing potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S), has improved tomato (*Solanum lycopersicum* L.) production in Brazil but a specific response by tomato to the S in PH is not confirmed. We compared four S sources – PH, sulfate of potash (SOP), sulfate of potash magnesia (SOPM), and single super phosphate (SSP) – applied at a target application rate of 40 kg S ha^{-1} to fertilizers with no S (muriate of potash, MOP), and no K or S at commercial application rates in three commercial fields in Brazil with nitrogen (N), phosphorus (P), and K applied at recommended rates of 355, 500, and 200–300 kg ha^{-1}, respectively. Consistent across locations, PH increased total yields over the control, MOP, and SSP, with SOP and SOPM higher than the control but not MOP or SSP. Only PH increased marketable yields compared to the control. Yields increased linearly with fruit numbers per plant which were higher for PH than the control or MOP, indicating higher fruit set in PH contributed to yield differences. While fertilizers increased leaf K and S concentrations and soil test K and SO_4–S, yield differences did not appear to be related solely to either K or S fertilization, nor to Mg fertilizers to which there was no response. Leaf and fruit Ca concentrations were higher in PH than the control and MOP at some locations suggesting Ca improved fruit set in PH. Results suggest tomato likely responded to the multinutrient content or solubility pattern of PH.

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calcium; fertilizer; fruit quality; magnesium; multinutrient; potassium

Introduction

Polyhalite (PH) has been shown to be a viable fertilizer for tomatoes (*Solanum lycopersicum* L.) and potatoes (*Solanum tuberosum* L.) in Brazil when compared to other potassium (K) source fertilizers as muriate of potash (MOP), sulfate of potash (SOP), and sulfate of potash magnesia (SOPM) (Mello et al. 2018a, 2018b). The studies by Mello et al. (2018b) and Sacks et al. (2017) did not isolate the individual nutrient effects from PH on tomato. PH is a multinutrient fertilizer containing sulfates of potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) with a guaranteed analysis of 14% K_2O, 19% S, 12% Ca, and 3.6% Mg (Kemp et al. 2016). Warren (2018) provides an overview of the geology of PH and its occurrence.

In Brazil, MOP is the most common K source, single super phosphate (SSP) or triple super phosphate (TSP) or monoammonium phosphate (MAP) are the primary P sources, and urea or ammonium sulfate (AS) are the common nitrogen (N) sources, with NPK blends applied at planting as basal dose with additional N and K applied as top dressing for crops. SSP and TSP contain Ca, SSP and AS contain S, and Mg is commonly applied through liming. The K_2O

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recommendations for fresh tomato for São Paulo State are 300 kg K_2O ha^{-1} for soils testing low in K (0–59 mg K kg^{-1}, and 100 kg K_2O ha^{-1} for soils testing high in K (>117 mg K kg^{-1}) reported by Trani and van Raij (1996). Gerendás and Führs (2013) recently reviewed the significance of Mg for crop quality and concluded there was an inconsistency in results of studies evaluating Mg in tomato quality and expressed the need for more research to improve our understanding of the importance of Mg nutrition on metabolite translocation and fruit quality in commercial tomato production. In tomato, Mg deficiency often occurs in plants and there is a known antagonism between Mg and K or Ca with an optimal K/Mg and Ca/Mg ratio required for high production and quality (Hao and Papadopoulos 2003). Recently, Kasinath, Ganeshamurthy, and Nagegowda (2015) reported Mg application to tomato on a soil with a soil test of 62 mg Mg kg^{-1} increased fruit yield, number, and weight of fruits with an optimum application of 50 kg Mg ha^{-1}. For Ca, despite significant application of Ca through lime and gypsum applications which are required periodically to ameliorate soil pH and aluminum (Al) toxicity in the highly acid soils of Brazil (Buol 2009; Fageria and Baligar 2008), the need for Ca fertilizer in addition to lime and gypsum application in tomato production was recently identified by Nowaki et al. (2017). Their study evaluated over-fertilization of P and nutrient imbalance of irrigated tomato crops in Brazil and concluded that yields were apparently not limited by P but limited by Ca which although supplied by lime and TSP was insufficient to increase the tomato yield. The addition of materials containing Ca, notably gypsum, can convert soluble P in soils to less soluble forms as the increased concentration of Ca^{2+} reduces the solubility of P by enhancing precipitation of insoluble Ca phosphates (Moore and Miller 1994). While the addition of Ca reduces P in runoff and leaching (Favaretto et al. 2012; King et al. 2016; Watts and Torbert 2016), gypsum is generally considered an excellent source of Ca and S that does not pose a threat to the environment or agronomic responses of crops (Kost et al. 2018; Watts and Dick 2014). The large effect of Ca on amelioration of subsoil acidity is most important to crop production in the Oxisol soils of Brazil (Buol 2009; Fageria and Nascente 2014) and makes the periodic addition of gypsum essential.

The addition of S fertilizers to crops is recently becoming more common throughout the world as the frequency of S deficiency of crops is increasing on a worldwide scale most often related to reduced S deposition from the atmosphere, the use of low-S containing fertilizers, the reduction in S-containing fungicides and pesticides, and higher crop yields (Scherer 2009). A report by TPS (2011) states that under tropical and subtropical conditions the critical concentrations of available SO_4–S vary with depth and clay content, which for the 0–20 cm depth are 3.0 and 9.0 mg kg^{-1} for soils with clay contents <400 and >400 g kg^{-1}, respectively, and for the 20–40 cm depth range are 10.0 and 35.0 mg kg^{-1} for clay contents <400 and >400 g kg^{-1}, respectively. Sfredo and Moreira (2015) reported soybean yield response to S fertilizer at soil test levels greater than the 10 mg kg^{-1} indicated as the adequate concentration for soybean plant. Malavolta (2006, as quoted in Sfredo and Moreira 2015), report that 90% of tropical soils, especially those in Cerrado regions, have subcritical SO_4–S concentrations. Tomato response to S fertilizer have recently been reported (de Souza Silva et al. 2014; Esmel et al. 2012; Kalpana, Suma, and Nagaraja 2015; Santos et al. 2007). For example, de Souza Silva et al. (2014) reported increases of 23–34% with S application as gypsum in a greenhouse pot study, with most of the increase realized by the 40 mg S kg^{-1} application rate. In Brazil, a shift from AS and SSP to more highly concentrated nutrient sources such as urea for N and TSP or MAP for P limits S additions from commercial fertilizers. While gypsum is applied but only periodically, S availability may be limited to the year of application since liming increases the SO_4–S leaching (Nodvin, Driscoll, and Likens 1986) and SO_4–S is readily leached in sandy soils and high rainfall areas of Brazil (Tiecher et al. 2013). A question regarding PH as multinutrient fertilizer is to what extent it is an S source for crops like tomato that could be applied at recommended rates of S while providing a portion of the K fertilizer requirement along with collateral benefits of the Ca and Mg to ameliorate subsoil Al toxicity as achieved by gypsum application commonly done in Brazil as well as supply these nutrients to tomato

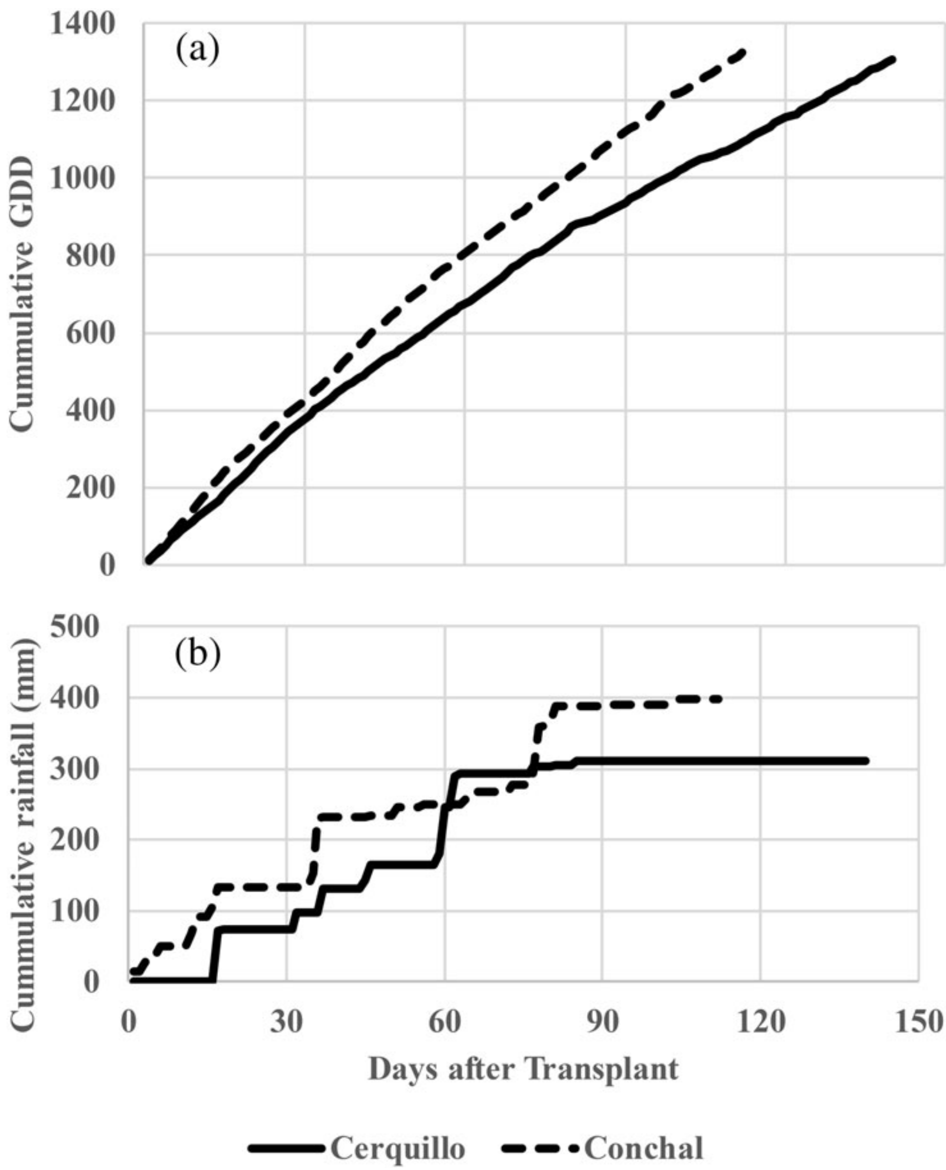

Figure 1. Growing season (a) cumulative growing degree days (GDD) and (b) cumulative rainfall during the growing season at Cerquilho and Conchal I São Paulo State, Brazil (summarized from data for Cerquillho at http://www.esalq.usp.br/departamentos/leb/postoaut.html and for Conchal at http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesAutomaticas).

(Nowaki et al. 2017). The S fertilizer recommendation for tomatoes in Brazil is between 20 and 40 kg S ha^{-1} (Trani, Nagai, and Passos 1997; Trani et al. 2015). An application of 40 kg S ha^{-1} as PH would provide 29, 25, and 7 kg ha^{-1} of K_2O, Ca, and Mg, respectively. For that S application rate, SOP and SOPM would provide 118 and 38 kg K_2O ha^{-1}, SOPM would provide 20 kg Mg ha^{-1}, and SSP would provide 53 kg Ca ha^{-1}.

This study compared PH as an S source to SOP, SOPM, and SSP when blended with MOP as the primary K source, with N and P applied as urea and MAP to eliminate S from other fertilizers. The hypothesis was that if S was deficient and S was supplied similarly by all S source fertilizers, tomatoes would respond to all blends containing S equally. If Mg was deficient, tomatoes would respond best to PH and SOPM and if Ca was deficient, tomatoes would respond best to

Table 1. Preplant soil test levels at the three experimental sites.

			mg kg^{-1}				
Site	Geo-reference	pH	P	K	Ca	Mg	S
Cerquilho1	23°10′31.8″ S 47°41′22.2″ W	5.5	10.3	86	254	63	6.6
Cerquilho2	23°10′31.8″ S 47°41′22.2″ W	5.4	9.7	63	202	52	6.4
Conchal	22°31′44.53″S 47°06′22.22″ W	5	8.4	82	320	117	7.7

Values are averages of all plots within a location.

PH and SSP. The study was repeated in three commercial tomato fields in São Paulo State, Brazil, a major producing state in Brazil (Makishima and de Melo 2009), to assess the consistency of response over multiple growing environments.

Materials and methods

Experimental sites

Experiments were conducted in two commercial tomato growers' farms located in São Paulo State, Brazil, one 23 km southeast of Conchal city, (22°31′44.53″ S, 47°06′22.22″ W) from 3 March through 7 July 2017, and another 5 km west of Cerquilho city (23°10′31.8″ S, 47°41′22.2″ W) from 21 March through 22 August 2017. Two experiments were conducted on the same farm but different fields in Cerquilho (Cerquilho1 and Cerquilho2). The growing season weather was warmer at Conchal with much higher growing degree days (GDD) accumulated in a shorter time period at Conchal than Cerquilho (Figure 1a) with slightly higher rainfall at Conchal (Figure 1b).

Soils in each experimental plot were sampled prior to each study by collecting a composite sample comprised of 15 random subsamples from the 0–20 cm depth, 20 February 2017 at Conchal and 13 March 2017 at both Cerquilho sites. The samples were mixed, air dried, and ground to pass a 2 mm sieve. Samples from each experimental unit were analyzed at the soil laboratory "Pirasolo", located in Piracicaba, São Paulo, Brazil, for pH ($CaCl_2$ 0.01 mol L^{-1}), P, K, Ca, and Mg (ion exchange resin extraction), and SO_4–S (Ca $(H_2PO_4)_2$ 0.01 mol L^{-1}) and total acidity H + Al (calcium acetate) (Raij et al. 2001). Pre-plant soil tests (Table 1) showed that for all three sites, soil pH was acidic, soil test P was low (<25 mg kg^{-1}), soil test K was medium (63–117 mg kg^{-1}), soil test Ca was high (>140 mg kg^{-1}), soil test Mg and S were medium (63–122 mg kg^{-1} and 5–10 mg kg^{-1}, respectively) for tomato production in Brazil (Raij et al. 1996). These soils are in the responsive range of soil SO_4–S (TPS 2011).

Treatments and experimental design

The experiment was a randomized complete block design with five replications at each of three locations consisting of six fertilizer treatments – MOP, MOP plus SSP, SOP, SOPM, or PH applied at a target application rate of 40 kg S ha^{-1}, and a control with no fertilizer K or S applied. Potassium fertilizer was applied as MOP adjusted for the K in the S fertilizer sources at application rates of 300 kg K_2O ha^{-1} at the Cerquilho sites and 200 kg K_2O ha^{-1} at Conchal. All treatments including the control received 500 kg P_2O_5 ha^{-1} as MAP adjusted for the P in SSP for that treatment and 256 kg N ha^{-1} including 55 kg N ha^{-1} in the MAP and the remainder as urea. Granular (2–4 mm diameter) PH was supplied by Sirius Minerals PLC (Scarborough, UK) while other fertilizers were obtained from commercial sources. Nutrients applied in fertilizers are summarized in Table 2.

Table 2. Nutrients supplied in fertilizers.

	kg ha^{-1}					
Nutrient	Control	MOP	PH	SOP	SOPM	SSP
N	256	256	256	256	256	256
P_2O_5	500	500	500	500	500	500
K_2O Cerquilho 1,2	0	300	300	300	300	300
K_2O Conchal	0	200	200	200	200	200
Ca	0	0	26	0	0	80
Mg	0	0	8	0	20	0
S	0	0	41	43	40	40
Cl Cerquilho 1,2	0	230	207	134	201	230
Cl Conchal	0	153	130	58	124	153

MOP, muriate of potash; PH, polyhalite; SOP, sulfate of potash; SOPM, potassium magnesium sulfate; SSP, single superphosphate.

Cultural practices

For this study, 40% of total $K_2O \pm S$ was applied in the crop row along with 100% of the P and 35% of the N prior to transplant of seedlings and incorporated by tillage to a depth 20 cm of soil depth. The remaining 60% of the $K_2O \pm S$ and N as urea was divided into eight equal application amounts and applied every 15 days after transplanting (DAT) as a top dress application in the row. At both Cerquilho locations, each plot consisted of 3.6 m of two rows spaced 1 m apart with plant spacings of 0.6 m for a total of 12 plants per plot with the cultivar Norte from Clause®. At Conchal, each plot consisted of 6 m of one row with row spacing of 1.5 m with plant spacings of 0.5 m for a total of 12 plants per plot with the cultivar Arendell from Nunhems®.

Tomato seedlings were cultivated in plastic trays filled with coconut fibers for 35 days in a greenhouse. The seedlings were transplanted on 21 March for both Cerquilho experiments and on 2 March for Conchal. At Conchal, the plants were grown with two stems in a vertical system using plastic strips while at Cerquilho they were grown in a bamboo inverted V system. The apical bud was cut when the plant reached the upper wire of the driving system.

Management practices for controlling insects and diseases of tomato plants were applied according to recommendations of Amorim, Rezende, and Filho (2011) and Gallo et al. (2002) for a Brazilian climate. Tomatoes were drip irrigated to reach soil moisture at field capacity when soil moisture monitored by a tensiometer indicated irrigation should be applied.

Foliar analysis

At Conchal, leaves were sampled 79 DAT on 19 May and at Cerquilho 71 DAT on 31 May at the beginning of reproductive phase. Seven leaves were collected per plot, sampling the third or fourth leaf from the growing tip of each plant. Leaves were rinsed with tap water, dipped in a phosphate free detergent solution (0.1% w/v), and rinsed three times with deionized water. Tissues were dried at 68 °C for 48 hr. Leaf samples were taken to the "Pirasolo" laboratory, at Piracicaba, SP, where they were ground and analyzed for N, P, K, Ca, Mg, and S according to Malavolta, Vitti, and Oliveira (1997).

Harvest

The first harvest was made when the first fruits turned red and tomatoes were harvested at intervals of 7 days. At Cerquilho, harvest began on 1 June with a total of 13 harvests. At Conchal, harvest began on 19 May with a total of eight harvests. Fruits were classified into four categories according to the transverse diameter: class 1A (small fruit, 40–50 mm), class 2A (average fruit, 50–60 mm), and class 3A (large fruit, >60 mm), and noncommercial (<40 mm). Tomato fruits

Table 3. Significant interactions for fertilizer source by location for tomatoes in Brazil.

	Fertilizer source					
Location	Control	MOP	PH	SOP	SOPM	SSP
	Non-marketable yields, kg ha^{-1}					
Cerquilho1	3.1 ab*	3.9 abc	3.2 ab	4.7 cd	3.7 ab	3.6 ab
Cerquilho2	3.3 ab	3.2 ab	4.0 bc	3.4 ab	3.0 a	3.3 ab
Conchal	5.2 d	5.0 d	5.2 d	5.6 de	7.0 f	6.3 ef
	Fruit number non-marketable					
Cerquilho1	9.6 abc	11.6 de	9.4 ab	13.7 fgh	12.4 efg	10.9 bcde
Cerquilho2	8.9 a	9.4 ab	11.4 cde	9.8 abcd	8.0 a	9.9 abcd
Conchal	10.8 bcde	12.5 efgh	12.7 efgh	11.9 efg	14.0 gh	14.3 h
	Total yield class 3A, kg ha^{-1}					
Cerquilho1	11.6 efg	11.3 efg	10.1 cdefg	11.9 efg	12.6 g	9.9 cdef
Cerquilho2	8.3 bcd	6.6 ab	8.0 bc	8.5 bcd	5.2 a	8.2 bc
Conchal	9.3 cde	10.9 defg	12.2 fg	6.5 ab	9.9 cdef	6.3 ab
	Brix/TA ratio at harvest					
Cerquilho1	11.8 c	9.0 a	9.9 ab	8.6 a	9.5 a	8.8 a
Cerquilho2	11.1 bc	9.8 ab	9.6 a	9.3 a	9.6 a	9.8 ab
Conchal	15.1 d	9.8 a	12.5 c	11.9 c	11.3 c	9.0 a
	Leaf Ca concentration g kg^{-1}					
Cerquilho1	9.9 ab	8.9 bcd	8.7 bcd	8.8 bcd	8.6 bcde	8.9 bc
Cerquilho2	7.1 cdef	6.3 ef	6.9 cdef	6.4 def	6.6 cdef	5.8 f
Conchal	10.9 ab	10.3 bcd	12.0 a	10.5 ab	9.8 bcde	10.7 ab
	Fruit Ca concentration at harvest, g kg^{-1}					
Cerquilho1	1.9 eg	1.9 eg	2.0 g	1.7 cdef	1.6 cd	1.6 cd
Cerquilho2	1.4 abc	1.5 cd	1.6 de	1.5 cd	1.6 cd	1.5 abcd
Conchal	1.2 ab	1.2 a	1.6 cde	1.6 cd	1.4 cd	1.4 bcd

Means within K sources followed by the same letter are not significantly different ($p > .05$).
MOP, muriate of potash; PH, polyhalite; SOP, sulfate of potash; SOPM, potassium magnesium sulfate; SSP, single superphosphate.

with blotchy ripening (Graywall), blossom-end rot, zippering, catfacing, and several other disorders were also classified as noncommercial. Total yield was determined as the sum of the weight of all fruits harvested throughout the harvest cycle. Commercial yield was determined as the sum of size classes 1A, 2A, and 3A.

Fruit analysis

Fruit for quality analysis was taken from the fruit harvested on the 4th harvest on 8 June at Conchal and the 5th harvest 29 June at Cerquilho. We collected 12 fruits per plot from the third or fourth fruit cluster from the base of each plant. The fruits were chopped, dried at 68 °C and taken into "Pirasolo" laboratory, at Piracicaba, SP, for the evaluation of nutrients N, P, K, Ca, Mg, and S according to Malavolta, Vitti, and Oliveira (1997).

Fruits for qualitative analysis (pH, titratable acidity (TA), total soluble solids (Brix), Brix/TA ratio, ascorbic acid, and firmness) were obtained on 29 June at all three sites. Six representative fruits per plot were ground and homogenized for the qualitative analyzes. Samples of homogenized fruit pulp were measured for Brix using a digital refractometer (Atago brand, model PR-32 α), and pH using a digital meter (Oakton model 110), TA was determined by titration of a dilute solution of the pulp with NaOH 0.1 mol L^{-1} until the solution reached a pH of 8.1 determined using a digital pH meter (Oakton model 110, Carvalho et al. 1990). The Brix/TA ratio was calculated as a measure of the characteristic flavor of the tomatoes where a higher value indicates a smoother flavor (Chitarra and Chitarra 2005). Ascorbic acid (vitamin C) content was determined using the method described by Carvalho et al. (1990). Fruit firmness was measured using the method of Hampson (1952) using an 8 mm tip obtaining two readings per fruit on opposite sides of his equatorial region.

Table 4. Significant effects of location for tomatoes in Brazil.

Category	Variable	Units	Location		
			Cerquilho1	Cerquilho2	Conchal
Yield	Total	t ha^{-1}	48.4 b*	40.6 a	73.2 c
	Marketable	45.1 b	37.1 c	68.1 a	
	1A	8.8 b	7.4 a	18.2 c	
	2A	25.4 b	22.4 a	40.7 c	
Fruit number	Total	# $Plant^{-1}$	51.7 b	44.1 a	54.4 b
	Marketable	40.8 b	34.1 a	41.7 b	
	1A	12.5 b	10.7 a	15.8 c	
	2A	21.8 b	18.8 a	22.2 b	
	3A		6.7 c	4.6 b	3.7 a
Average fruit weight	Total	G	94 b	92 b	122 a
	Marketable		110 b	107 b	147a
Quality at harvest	Ascorbic Acid	mg 100 g^{-1}	10.2 a	10.8 a	14.7 b
	Titratable acidity		0.38 b	0.38 b	0.34 a
	pH		4.42 a	4.42 a	4.49 b
	Firmness	N	39.8 b	42.5 c	33.8 a
Leaf nutrient concentrations	N	g kg^{-1}	38.2 a	39.4 a	45.3 b
	P		4.0 b	3.9 b	3.1 a
	Mg		3.4 a	3.3 a	4.1 b
	S		3.4 c	2.7 a	3.1 b
Fruit nutrient concentrations at harvest	N	g kg^{-1}	32.1 b	31.1 b	27.9 a
	P		5.9 c	5.1 b	4.0 a
	K	40.9 c	37.3 b	31.0 a	
	Mg		2.4 b	2.6 b	1.9 a
	S		2.26 b	1.91 a	1.69 a
Changes in soil tests	K	mg kg^{-1}	137 a	125 a	211 b
	Mg		−14 b	−17 b	−33 a

Means within location followed by the same letter are not significantly different ($p > .05$).

Post-harvest soil sampling

Following the same procedures described for the preplant soil sampling, soil samples were collected on 12 July at Conchal and 22 August at Cerquilho from each plot and analyzed for pH, P, K, Ca, Mg, and SO_4–S.

Statistical analysis

The experiment was analyzed as a two-factor factorial using a fixed-effects model with the intent that conclusions from this study are not to be generalized to other fertilizers or locations. We used Fishers unprotected LSD at the 5% significance level when *F*-tests indicated that significant differences existed ($p < .05$).

Results

Interactions

Our main interest was whether PH was an adequate S source for tomato production and if the response was consistent across locations. Of the 37 variables analyzed, six showed a significant fertilizer source by location interaction at $p < .05$ associated with differences between sites as well as differences due to fertilizer source within a site (Table 3). We will discuss these interactions in the discussion of main effects of fertilizer source. A summary of significant differences due solely to locations is provided in Table 4 and significant differences due solely to fertilizer source in Table 5.

Table 5. Significant effects of fertilizer source for tomatoes in Brazil.

			Source					
Category	Variable	Units	Control	MOP	PH	SOP	SOPM	SSP
Yield	Total	t ha^{-1}	50.3 a	53 ab	57.1 c	55.1 bc	56.2 bc	52.9 ab
	Marketable		46.4 b	48.5 ab	52.9 a	51.2 ab	51.7 ab	49.8 ab
	1A		8.8 a	11.2 b	12.5 c	12.0 bc	12.5 c	11.7 bc
Fruit number	Total		44.4 a	48.8 b	53.6 d	50.8 bc	51.8 cd	51.1 bcd
	Marketable	Plant^{-1}	34.9 c	37.5 bc	42.2 a	39.8 ab	40.1 ab	38.8 abc
	1A		10.03 a	12.29 b	14.35 c	13.47 bc	14.22 c	13.65 c
Fruit quality at harvest	TA	mg 100 g^{-1}	0.30 a	0.40 cd	0.35 b	0.37 b	0.38 bc	0.41 d
Leaf nutrient concentration	P	g kg^{-1}	3.5 a	3.6 ab	3.6 ab	3.7 ab	3.7 b	4.0 c
	K		25.3 a	30.4 b	33.2 c	32.0 bc	32.4 bc	32.1 bc
	S		2.7 a	2.7 a	3.4 c	3.1 b	3.1 bc	3.2 bc
Fruit nutrient concentrations at harvest	N	g kg^{-1}	29.3 a	29.5 a	30.4 ab	32.6 c	28.9 a	31.6 bc
Changes in soil test	K	mg kg^{-1}	−31 a	207 bc	231 c	215 c	160 b	164 b
	Ca		−38 bcd	−58 abc	−34 cd	−78 a	−62 ab	−28 d
	SO_4–S		−3.3 a	−1.9 a	0.6 b	6.2 c	0.8 b	2.3 b

Means within K sources followed by the same letter are not significantly different ($p > .05$).
MOP, muriate of potash; PH, polyhalite; SOP, sulfate of potash; SOPM, potassium magnesium sulfate; SSP: single superphosphate.

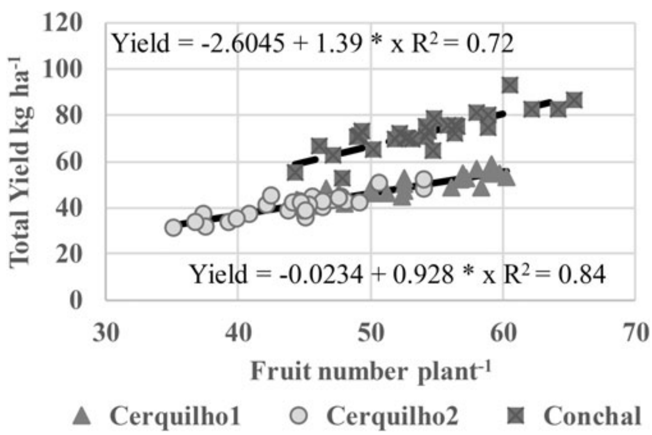

Figure 2. Regression of fruit number per plant on total yield of tomato for the two locations from Cerquilho and from the Conchal location in São Paulo State, Brazil.

Fertilizer source

Although tomato yields varied by location (Table 4), there were no interactions between fertilizer source by location. Total yields were consistently higher for PH than the control, MOP, and SSP with yield differences reflecting higher total fruit numbers per plant associated in part with higher fruit numbers and yields of 1A tomatoes for PH (Table 5). Total yields increased linearly with fruit number with a single regression line for the two Cerquilho locations and a different regression line at Conchal (Figure 2). Marketable yield was higher than the control only for PH which also had higher marketable fruit numbers per plant than the control and MOP (Table 5). There were no differences in fruit number or yield of class 2A tomatoes due to fertilizer source. While fruit number of class 3A tomatoes were not affected by fertilizer source, yield of class 3A tomatoes varied with fertilizer source and location with PH showing higher yields of class 3A tomatoes at Conchal than the control, SOP, and SSP (Table 3). Non-marketable yield and fruit number varied by fertilizer source and location with similar yields for PH and the control and MOP and higher or lower marketable fruit numbers than the other treatments depending on location (Table 3). While there was no effect of fertilizer on average fruit weight for either total or marketable yield, fruit weight was approximately 16–20% higher for marketable than total yield with both higher at Conchal (Table 4).

Fruit quality at harvest showed no differences in ascorbic acid, pH, Brix, or firmness at harvest due to fertilizer source. All fertilizer sources increased TA compared to the control with slight differences among fertilizer sources with TA higher for SSP than PH, SOP, and SOPM and higher for MOP than PH and SOP (Table 5). The Brix/TA ratio was highest for the control at Cerquilho1 and Conchal but similar for MOP and SSP and the control at Cerquilho2 (Table 3). There were no differences in Brix/TA ratio among fertilizer sources at either Cerquilho location but at Conchal, MOP and SSP had the lowest Brix/TA ratio (Table 3).

Response of leaf nutrient concentrations to fertilizer source varied by nutrient and to some extent location (Tables 3–5). Leaf N and Mg concentrations were not affected by fertilizer source within any location but were higher at Conchal than either Cerquilho location (Table 4). Leaf P concentrations were higher in SSP than all other treatments and higher in SOPM than the control (Table 5), with Conchal lower than either Cerquilho location (Table 4). All fertilizers increased leaf K concentrations over the control with higher leaf K concentrations in PH than MOP but similar concentrations to other fertilizer sources (Table 5). Leaf Ca concentrations were not affected by fertilizer source at either Cerquilho location but were higher for PH than MOP and SOPM at Conchal (Table 3). Leaf Ca concentration had the highest correlation to total and marketable yield ($r = 0.72$ and 0.73, respectively). Leaf S concentrations were increased by the addition of S as PH, SOP, SOPM, and SSP all had higher S concentrations than MOP and the control with slightly higher leaf S concentrations in PH than SOP (Table 5).

Fruit N concentrations at harvest were higher in SOP than all but SSP and higher in SSP than the control, MOP, and SOPM (Table 5). There were no effects of fertilizer source on fruit P, K, Mg, or S concentrations at harvest but these were all lowest at Conchal where yields were higher and highest at Cerquilho1 (Table 4). Fruit Ca concentrations at Cerquilho1 were higher for PH than SOP, SOPM, and SSP but similar to the control and MOP, with SOP similar to the control and MOP (Table 3). At Cerquilho2, PH had higher fruit Ca concentrations than the control but similar concentrations to all fertilizer sources. At Conchal, fruit Ca concentrations were higher in PH, SOP, and SOPM than the control or MOP, with SSP similar to the control but higher than MOP.

Changes in soil tests

Fertilizer source did not affect soil pH or soil test P and Mg. Overall, soil pH declined 0.9 units, soil test P increased an average of 128 $mg\,kg^{-1}$, and soil test Mg declined slightly depending on location (Table 4). As expected, K fertilizer application increased soil test K for all fertilizer sources while soil test K declined in the control, increasing more for PH and SOP than SOPM and SSP, with MOP similar to all other fertilizer sources (Table 5). Soil test Ca declined overall but the decline was higher for SOP than all but SOPM, lower for SSP than MOP, and similar for PH, MOP, and SSP to the control (Table 5). The addition of S fertilizer increased soil test SO_4–S slightly for PH, SOPM, and SSP but much more for SOP while soil test levels declined similarly for the control and MOP (Table 5). Changes in soil test levels were similar for all locations for P, Ca, and SO_4–S but soil test K increased and soil test Mg declined more at Conchal (Table 4).

Discussion

The response to PH confirms the report by Mello et al. (2018b) for the Cerquilho location who attributed the yield differences to the Ca in PH. While PH increased total yield over the control, it appears that there was no yield response to K fertilizer application in spite of initial soil test K levels in the responsive range given there were no differences in total yield for the other fertilizer sources and the control. A response to K fertilizer was expected given the rate response reported by Mello et al. (2018b). Based on Hochmuth et al. (2004), leaf nutrient concentrations were in the deficient range for the control for K ($<30\,g\,K\,kg^{-1}$) suggesting K fertilizers increased K uptake during the growing season. Leaf K concentrations were similar to those reported by Huang and Snapp (2009), Mello et al. (2018b), and Taber (2006) who reported K leaf concentration increased with K fertilization rate. Brewer et al. (2018) reported sufficient leaf K concentrations ($>30\,g\,K\,kg^{-1}$) 12 weeks after planting but only when K was applied at or above recommended rates in the first year of their study and less than sufficient in the next two growing seasons regardless of K applied. While leaf K concentrations were higher than the control for all fertilizer sources and higher in PH than MOP, these differences were not observed in the fruit at harvest. The increase in leaf K concentrations by PH over MOP is consistent with Mello et al. (2018b) for the Cerquillo location although they reported PH increased fruit K concentrations. At harvest, there were no treatment effects on fruit K concentrations which were slightly higher than the 28–32 $g\,K\,kg^{-1}$ reported by Kinoshita and Masuda (2011) and concentrations reported Mello et al. (2018b). Tomato yield response to K fertilizer is well documented (Davies and Winsor 1967; Javaria et al. 2012; Zhu et al. 2017) and K is known to improve tomato fruit quality (Dorais, Papadopoulos, and Gosselin 2001) such that high K application rates are often applied for tomato production in São Paulo State (Trani et al. 2015) and around the world (Chen et al. 2004; Hochmuth et al. 2004). Daily applications recommended for irrigated tomatoes ranging from 1.7 to 2.8 $kg\,ha^{-1}\,day^{-1}$ (Warncke, Dahl, and Zandstra 2004) and 0.9 to 1.8 $kg\,K\,ha^{-1}\,day^{-1}$ (Hartz and Hochmuth 1996). Therefore, a yield response to K fertilizer was expected in these studies but the yield difference associated with PH was apparently not due to K.

The addition of S alone was not sufficient to increase yields over the control as only PH showed significance in yields and not the other S fertilizer sources. Based on Hochmuth et al. (2004), leaf S concentrations were in the deficient range for the control and MOP for S ($<3\,g\,S\,kg^{-1}$) but sufficient for all S fertilizer treatments. However, leaf S concentrations were in the low end of the sufficiency range of 2–10 $g\,S\,kg^{-1}$ reported by Orman and Kaplan (2009) and lower than the 5–11 $g\,S\,kg^{-1}$ reported by Mello et al. (2018b), the 5.5–6.6 $g\,S\,kg^{-1}$ reported by Esmel et al. (2012), and the 5.3–7.9 $g\,S\,kg^{-1}$ reported by Santos et al. (2007) including their no S fertilizer control. The low leaf S concentrations suggest that a higher S fertilizer application rate could have been applied. Santos et al. (2007) reported S fertilizers increased marketable yields from 13.6 to 17.9 $t\,ha^{-1}$ although S was applied at very high application rates, 384 $kg\,S\,ha^{-1}$ as gypsum compared to 40 $kg\,S\,ha^{-1}$ in various sources in our study. Esmel et al. (2012) reported that while S fertilization did not affect leaf S concentrations it increased early yields on a sandy soil in Florida. De Souza Silva et al. (2014) in greenhouse pot studies in Brazil reported quadratic responses of leaf S concentration, dry matter content of the shoots, and tomato production per pot with S application rate over the range 20–100 $mg\,S\,kg^{-1}$ soil. As is the case with other crops, reports on a response of tomato to S fertilization are recent. However, it does not appear in this study that S fertilization alone was responsible for the significant yield response in PH.

The lack of yield response to K and S fertilizer suggests that the response to PH was due to the multinutrient composition of PH that included Ca and Mg in addition to K and S, although SOPM added more Mg and SSP added more Ca than PH. There is little evidence that the response to PH was due to Mg alone as the amount of Mg applied was low, the higher Mg addition from SOPM did not significantly increase yields, neither leaf or fruit Mg concentrations were affected by fertilizer application, and while soil test Mg declined an average of 21 $g\,Mg\,kg^{-1}$ there were no differences in soil test Mg due to fertilizer application. Mello et al. (2018b) reported no effect of fertilizer source on leaf Mg concentration, a slight increase in fruit Mg concentration at harvest with PH, and increased soil test Mg but at much higher fertilizer application rates. Leaf Mg concentrations were in the adequate range (3–5 $g\,Mg\,kg^{-1}$) for all treatments but lower than reported by Mello et al. (2018b) and there were no treatment effects in fruit Mg concentration similar to Davies and Winsor (1967) who reported Mg and lime had little effect on tomato fruit composition. Fruit Mg concentrations were higher than the 1.4–1.5 g Mg kg^{-1} reported by Kinoshita and Masuda (2011) and slightly higher than the 1.8–1.9 g Mg kg^{-1} reported by Mello et al. (2018b). Consequently, Mg alone appeared not to be a factor in tomato response to fertilizer application as evidenced by the lack of response to SOPM compared to MOP.

Because Ca along with K and B are the key nutritional factors controlling fruit development and maturation (Marschner 2012), Ca in PH may have been important in the yield response by tomato to PH. Keep in mind that the Ca and S in SSP are in the form of gypsum which has much lower solubility than PH and may have been less available from SSP than from PH. Leaf Ca concentrations were deficient according to Hochmuth et al. (2004) for all treatments at both Cerquilho sites (<10 g Ca kg^{-1}), lower than the 14–21 g Ca kg^{-1} reported by Mello et al. (2018b) for Cerquilho, adequate but at the low end of sufficiency at Conchal (10–20 g Ca kg^{-1}). Fruit Ca concentrations were slightly lower than reported by Mello et al. (2018b) for the Cerquilho location and lower than the 2.6 g Ca kg^{-1} reported by Kinoshita and Masuda (2011) although fruit N, P, K, and Mg concentrations were higher in our study. PH increased Ca concentration in the leaf and fruit compared to other fertilizers and the control but that varied by location. Leaf Ca concentrations were higher for PH than MOP or SOPM at the Conchal location but not the control and were overall moderately correlated with yield. Fruit Ca concentrations for PH were always at the highest value at all three locations. Also, post-harvest soil test Ca declined more for MOP, SOP, and SOPM than for PH and SSP and the control treatments suggesting the Ca in PH and SSP offset the effect of high application rates of K fertilizer on soil test Ca levels as reported by Nachtigall, Carraro, and Alleoni (2007) after 12 years of K fertilizer application in Brazil. While not possible to confirm from this study, the response to PH may be associated with the combination of nutrients provided by PH perhaps through increased flowering or fruit set as evidenced by higher fruit numbers in PH and the strong linear relationship between fruit number and yield consistent with the high correlations reported by Mello et al. (2018b). Mutka, Rahman, and Mortuza (2015) reported data that show a strong relationship between fruit number per plant and tomato yield for a high yielding variety BARI Tomato-14 developed for Bangladesh. Higher fruit numbers may reflect lower incidence of blossom-end rot associated with Ca (Ho and White 2005; Taylor and Locascio 2004).

Tomato quality at harvest was generally in the range reported in the literature, with differences due to fertilizer source only for TA, fruit N and Ca concentrations, and the sugar–acid ratio. Fruit pH at harvest was at or slightly below 4.5, a desired trait (Tigist, Workneh, and Woldetsadik 2013), similar to other studies (Djidonou et al. 2016; Stevens, Kader, and Albright 1979; Zhu et al. 2017). Ascorbic acid was in the range reported by Tigist, Workneh, and Woldetsadik (2013) but lower than the range reported by others (Toor and Savage 2006; Djidonou et al. 2016) and much lower than the range reported by Mello et al. (2018b). TA in the control was low and below the 0.32 mg 100 g^{-1} level considered by Kader et al. (1978) to be characteristic of high-quality fruit. TA values were similar for field grown tomatoes to those reported by Tolesa and Workneh (2017), Turhan and Seniz (2009), and Djidonou et al. (2016) but lower than values reported by Duma et al. (2017), Tigist, Workneh, and Woldetsadik (2013), and Yeshiwas and Tolessa (2018). Brix was not affected by fertilizer source as reported by Mello et al. (2018b) or by location. The average Brix of 3.7% is slightly lower than Mello et al. (2018b) and comparable to Aoun et al. (2013), Djidonou et al. (2016), and Zhu et al. (2017) but lower than Kader et al. (1978) for vine ripened tomatoes, Cantwell (2010) for ripe tomatoes purchased at supermarkets, and for 33 genotypes in Turkey (Turhan and Seniz 2009). The sugar–acid ratios are comparable to Kader et al. (1978), Lambeth, Fields, and Huecker (1964), and Cantwell (2010) but much higher than Tigist, Workneh, and Woldetsadik (2013) for fresh market tomatoes and somewhat lower than the range calculated from Djidonou et al. (2016). Ratios were generally higher in the control than fertilized tomatoes at all locations suggesting fertilizers reduced ratios in this study. Higher ratios for PH, SOP, and SOPM than MOP and SSP at Conchal suggest fertilizer source effects at higher tomato yields.

Fruit nutrient concentrations were in the range reported by Raleigh and Chucka (1944) but fruit K, Mg, and S were higher and Ca lower than reported by Mello et al. (2018b) for the Cerquilho location. Only fruit N concentrations were affected by fertilizer source but the differences do not explain the response to PH. N concentrations were similar to those reported by Brewer et al. (2018) but more than double the range reported by Kinoshita and Masuda (2011) and much higher than Mutka, Rahman, and Mortuza (2015). While fruit K and Mg concentrations were not affected by fertilizer source in this study, fruit K concentrations were higher for PH than all but SOPM in the Mello et al. (2018b) study at the Cerquilho location. Fruit Ca concentrations in this study were lower than the ranges reported by Kinoshita and Masuda (2011) and Mutka, Rahman, and Mortuza (2015) and slightly lower than reported by Mello et al. (2018b). However, fruit Ca concentrations were higher for PH than the other S source fertilizers at Cerquilho1, PH was the only S fertilizer higher than the control at Cerquilho2, and all S fertilizer sources had higher fruit Ca concentrations at Conchal. While not conclusive, the response of fruit and leaf Ca concentrations to fertilizer source suggests Ca may have contributed to the observed yield response to PH as suggested by Mello et al. (2018b) that may be associated with the observed higher fruit numbers in response to Ca through its influence on blossom-end rot (Ho and White 2005; Taylor and Locascio 2004).

Interactions between the nutrients in PH and with other nutrients are agronomically important and the literature is extensive with numerous reviews (Fageria 2001; Pan 2012; Rietra et al. 2017). The antagonism among K, Ca, and Mg in tomato is well documented (Gunes, Alpaslan, and Inal 1998; Hao and Papadopoulos 2003; Voogt 1988) and in soil, as reported by Kost et al. (2018) who showed gypsum lowered Mg concentrations in soil due to the replacement of Mg by Ca resulting in leaching of Mg and other nutrients. However, the antagonism among K, Ca, and Mg may not be as important in Brazilian soils where periodic additions of lime and gypsum are required to manage soil pH and subsoil acidity (Fageria and Baligar 2008), supplying large quantities of Ca, Mg, and S, and because annual K fertilizer applications for tomato are high (Trani and van Raij 1996). Furthermore, annual applications of Ca, and S in fertilizers including SSP, TSP, and AS are common and has not been identified as problematic for Brazilian crop production. The interaction of S and Fe is also important in tomato production. Astolfi et al. (2003) reported lower Fe accumulation in leaves of S-deficient maize plants which was later confirmed in tomato by Zuchi et al. (2009, 2015) who reported that limited availability of S reduces the iron uptake and deficiency of iron also results in modulation of sulfur uptake in tomato. The common and substantial application of Ca, Mg, and S in lime and gypsum and in common fertilizer sources used in Brazil for tomato production suggest the addition of these nutrients along with K in PH would have similar results.

Conclusion

Consistent across locations, tomato responded to PH but not to other fertilizers in total and marketable yields and higher fruit numbers per plant that clearly increased yields. While fertilizers increased leaf K and S concentrations and soil test K and SO_4–S levels, these nutrients did not appear responsible for the response to PH. Since leaf and fruit Ca concentrations were higher in PH than the control and MOP, results suggest tomato likely responded to the multinutrient content or solubility pattern of PH as there was no yield response to K, K + S, K + S + Mg, or K + S + Ca provided in the MOP, SOP, SOPM, and SSP fertilizers, respectively. The lack of response to K was not expected given the soil test K levels were in the responsive range and given the high demand for K by tomato. A response to S was also expected given the low pre-plant soil test SO_4–S levels and recent studies showing tomato response to S fertilizers on low testing soils.

Although above sufficiency levels, low leaf and fruit S concentrations suggest tomatoes may have responded to higher application rates of S fertilizer. Since PH contributed only 9% of the K compared to 42% and 13%, respectively for SOP and SOPM, it may be economical and advantageous to increase the % of PH in the MOP blend to determine if increasing the S, Mg, and Ca applied would enhance the effect observed in this study.

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Declaration of interest

Dr. Pavuluri was employed by Sirius Minerals PLc as the scientist/agronomist assigned to this project and facilitated the funding for this project. Dr. Pavuluri is no longer employed with Sirius Minerals PLc but is a stockholder in the company. Dr. Pierce works as a consultant with Sirius Minerals PLc.

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