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Effect of sulphur dose on the productivity and quality of onions

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Abstract

Onions have a high demand for sulphur (S), which affects bulb productivity and quality. S, however, should be carefully applied to onion crops because it may acidify the soil and adversely affect the plants. This study evaluated the effects of S dose (0, 15, 30, 45, 60, and 90 kg ha^{-1}) on the soil and the development, productivity, and quality of the 'Perfecta' onion cultivar. The experiment was conducted in Jaboticabal, Brazil, from 30 May to 10 October 2011. Maximum height (0.76 m), number of leaves per plant (7.2), dry weight of leaves (201.6 g), and productivity (79 t ha^{-1}) of the 'Perfecta' onions were obtained with doses of 57, 41, 47, and 45 kg S ha^{-1}, respectively. Onion productivity was 16% lower, when S was not applied. About 47% of total production of bulbs was ranked in classes 3 and 4, with higher commercial value. The highest percentage of bulbs (63%) in classes 3 and 4 was obtained with 47 kg S ha^{-1}. Maximum pungency (1.5 µmol g^{-1}) was obtained with 65 kg S ha^{-1}, ca. 55% higher than when S was not applied. The levels of pyruvic acid, however, were low in all treatments, which ranked the cultivar as very mild with an extra-sweet flavour when provided with up to 90 kg S ha^{-1}. The interaction between S dose and period of evaluation influenced the soil pH and S content. The increased S supply increased the levels of foliar N and S-SO_4^{2-} and decreased Ca^{2+} and Mg^{2+}.

Keywords: *Allium cepa* L.; elemental S; fertilisation; pungency; pyruvic acid; mineral nutrition.
Abbreviations: LD_diameter; DAS_days after sowing; DML_dry mass of leaves; HGT_height; L_length; LP_number of leaves per plant.

Introduction

Onions (*Allium cepa* L.) belong to the family Alliaceae and are widely cultivated as an important crop among the vegetables and spices (Mishu et al., 2013). Onions are of high socioeconomic importance in Brazil and are the third most important vegetable crop in the country, behind only tomatoes and potatoes (IBGE, 2014). The amount paid to the producer is determined by the size, quality, and health of the onion bulb, and these attributes are directly related to plant nutrition, particularly the supply of nitrogen (N), phosphorus (P), potassium (K), and sulphur (S) (Kurtz and Ernani, 2010). Onions require high amounts of S (Porto et al., 2007, Mishu et al., 2013), and less than an optimal supply to different plant tissues can limit crop growth at any stage, resulting in low yields (Mishu et al., 2013). S fertilisation can also affect bulb quality, especially its pungency, which is defined as the combination of onion flavour and odour that are functions of the concentrations of sulphonic and thiosulphonic volatile acids containing S (Schünemann et al., 2006). Pungency is classified by alliinase activity, expressed in µmol of pyruvic acid g^{-1} of onion , as too mild (0-2.9 µmol g^{-1}), mildly pungent (3.0-4.2 µmol g^{-1}), slightly pungent (4.3-5.5 µmol g^{-1}), pungent (5.6-6.3 µmol g^{-1}), strongly pungency (6.4-6.9 µmol g^{-1}), too pungent (7.0-7.9 µmol g^{-1}), and spicy (8.0-10.0 µmol g^{-1}). Onions are certified as extra sweet at pyruvic acid concentrations up to mildly pungent and as sweet at concentrations up to slightly pungent. The mechanism that produces the pungency is regulated by the genetic potential of the cultivars and involves the absorption of S and the synthesis of flavour precursors, which determine the overall flavour intensity (Randle, 1997; McCallum et al., 2001). The cultivars differ in their efficiency in absorbing soil S, the synthesis of the flavour precursors, and the concentration of alliinase (Randle, 1997).

Consumer demand has recently been oriented towards onion cultivars with low pungency (mild cultivars), but many factors, especially S-based fertilisation, may affect the accumulation of organosulphuric compounds in onions (Gallina et al., 2012) and consequently the flavour. Despite the importance of S to onion metabolism, some producers choose to use fertilisers with high concentrations of N, P, and K, which consequently have low S contents (Kunz et al., 2009), to reduce costs. The use of elemental S in fertiliser mixtures would be an alternative for increasing nutrient contents and meeting the needs of the onion plants (Horowitz, 2003). This study evaluated the effect of S dose on plant development and nutritional status, on the production, classification, and pungency of the bulbs, and on soil pH and S content.

Results and Discussion

Development and leaf analysis

Doses up to 57 and 41 kg S ha^{-1} had positive effects on plant height and number of leaves, attaining maximums of 75.9 cm and 7.2 leaves, respectively (Fig 1). These results may be related to the benefits of adequate S supplies to the plants, because low or excessive doses are detrimental to growth and crop development (Paula et al., 2002; Al-Fraihat, 2009; Mishu et al., 2013).

S dose had a significant effect on the dry mass of leaves (DML). The effect was polynomial with a quadratic adjustment, and the increase of S up to 47 kg ha^{-1} increased DML to a maximum of 201.6 g m^{-2} (Fig 1). This result was in accordance with that by Mishu et al (2013), who observed maximum levels of onion foliar dry matter at 40 kg S ha^{-1}. The dose that maximised DML was similar to the dose that produced maximum plant height and leaf number and also to the dose of 45 kg S ha^{-1} observed by Nasreen and Huq (2005), which maximised plant growth. Mishu et al. (2013) evaluated doses up to 80 kg S ha^{-1} and obtained the highest net assimilation rate by onion plants, and consequently higher leaf dry weights, at 40 kg S ha^{-1}. Our maximum DML was intermediate between the 182 g m^{-2} reported by Pôrto et al. (2006) and the 239 g m^{-2} reported by Pôrto et al. (2007) for 'Optima' and 'Superex' onions, respectively. 'Perfecta', however, produced a DML of 158.2 g m^{-2} when S was not applied (Fig 1), less than the amount obtained in the above studies. Significant adjustments of the quadratic effect were necessary for bulb diameter and length; doses of 58 and 64 kg S ha^{-1} produced the maximum diameter (65.0 mm) and length (82.3 mm) (Fig 1). Height, number of leaves, and DML responded similarly. This relationship with the other features is due to the structural role that S plays in plants, being present in many compounds, so that S fertilisation benefits onions, as also reported by Lancaster et al. (2001), Al-Fraihat (2009), and Haneklaus et al. (2014). Excessive amounts of S, however, adversely affect the growth and development of onions and, consequently, bulb formation (Paula et al., 2002; Mishu et al., 2013). Average bulb diameter remained within the range of consumer preference, 40-80 mm, and the bulbs retained a rounded shape. Even without the application of S, 'Perfecta' bulb diameter (59.4 mm) remained within this range, indicating that this cultivar is a good choice for areas with low nutrient levels. Foliar P and K contents were not significantly influenced by the S dose. The polynomial adjustment, however, was quadratic for foliar S content and linear for foliar N content, depending on the S dose to the soil (Fig 2). The increasing foliar N contents at increasing doses of S, also reported by Karimizarchi et al. (2014), may be associated with the synthesis of compounds such as amino acids, proteins, coenzymes, lipids, sulphoxides, and nucleotides, which contain S and N (Nasreen and Huq, 2005; Kunz et al., 2009). Higher S doses provide greater N absorption by the plants, indicating a positive interaction between these elements (Malavolta and Moraes, 2007; Haneklaus et al., 2014). Paula et al. (2002) found no increase in N content in onion leaves at higher S doses, but the foliar N:S ratio decreased with increasing doses of S. In our study, the N:S ratios were 6.7, 5.1, 4.7, 4.4, 4.4, and 4.1 at S doses of 0, 15, 30, 45, 60, and 90 kg ha^{-1}, respectively, corroborating the results obtained by Paula et al. (2002). The foliar N (Fig 2), P (3.8-4.9 g kg^{-1}), and K (25.2-26.3 g kg^{-1}) contents were within the normal ranges for onions of 20-30, 2-5, and 15-30 g kg^{-1}, respectively (Hochmuth et al., 2012). Foliar S content (Fig 2) was also within the normal range of 2-6 g kg^{-1} leaf dry matter (Hochmuth et al., 2012) for the range of doses evaluated. The maximum foliar S content was 79 kg ha^{-1}, reaching 6.1 g kg^{-1} of dry matter (Fig 2). Plant S content is positively correlated with soil elemental-S content due to the oxidation reactions that render the nutrient available to plants (Wen et al., 2003). Excess S available in the soil, though, adversely affects crop development and can be toxic. Paula et al. (2002) also observed this response at higher soil S-SO_4^{2-} contents, but using a highly water soluble source. Foliar calcium (Ca) and magnesium (Mg) contents were negatively correlated with S dose (Fig 2). Foliar Mg contents were within the normal range (Hochmuth et al., 2012) for onions, but foliar Ca contents were below the normal range, when the S dose was higher than 20 kg ha^{-1}. Foliar Ca and Mg contents decreased even when the soil was amended with bulk magnesium thermophosphate and other constituents in the fertiliser formulation (Fig 2). The lower foliar Ca and Mg contents may have been due to a dilution effect of these nutrients in the plants.

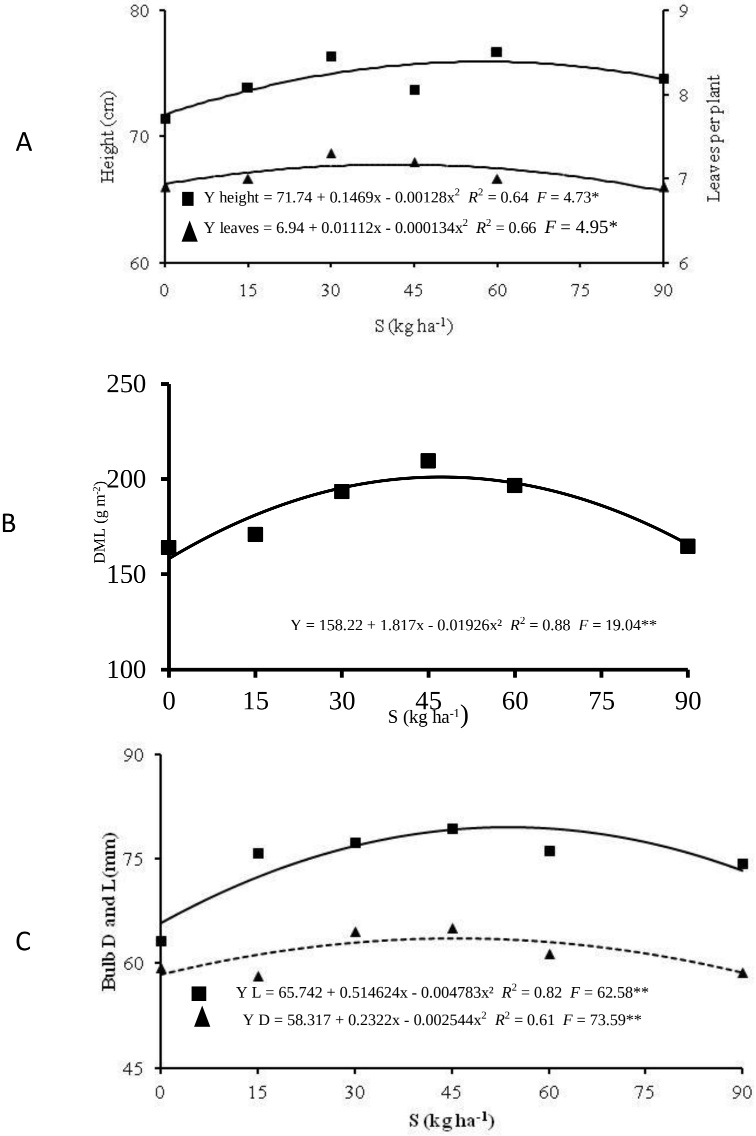

Fig 1. Plant height and number of leaves per plant (a), dry mass of leaves (DML) (b), and diameter (D) and length (L) of bulbs (c) of 'Perfecta' onions as functions of the sulphur dose 90 days after sowing.

Productivity and bulb classification

Productivity was influenced by S dose, and the quadratic polynomial equations required adjustments (Fig 3). Increasing the S dose increased productivity to a maximum of 79 t ha^{-1} at 45 kg S ha^{-1}, similar to that observed by Mishu et al. (2013) with 40 kg S ha^{-1}. Higher doses decreased onion

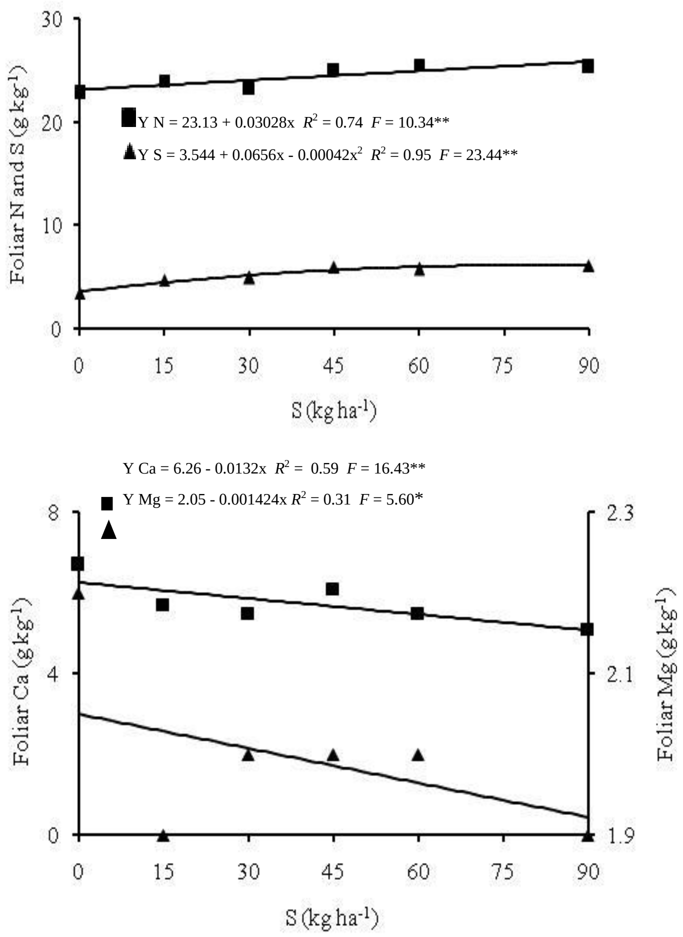

Fig 2. Foliar nitrogen (N) and sulphur (S) (a), calcium (Ca) and magnesium (Mg) (b) content in 'Perfecta' onions as functions of the S dose.

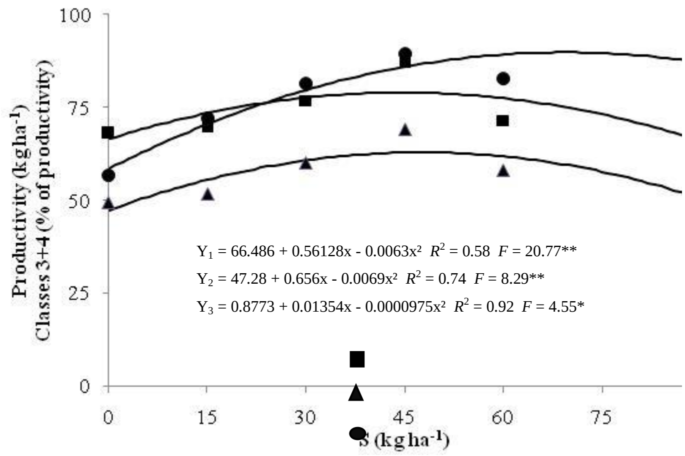

Fig 3. Productivity (Y_1), percentage of bulbs in classes 3 and 4 (Y_2), and bulb pungency (Y_3) of 'Perfecta' onions as functions of the sulphur dose.

production, which was also observed by Paula et al. (2002) at doses of 58 kg S ha^{-1}. Productivity was 13 t ha^{-1} lower when no S was applied, ca. 84% of the maximum (Fig 3). These results corroborate those by Al-Fraihat (2009). Doses higher than 41 kg S ha^{-1} must be applied to meet the S requirements of onions, which take up 31-34 kg S ha^{-1} (Pôrto et al., 2006; Pôrto et al., 2007). S is needed for all important plant functions and processes, including protein biosynthesis and hormonal control, which in addition to influencing growth and cell differentiation, indirectly interferes with crop productivity (Malavolta and Moraes, 2007). The quadratic polynomial equations for the percentage of bulbs in classes 3 and 4, which have higher commercial value, required significant adjustments (Fig 3). Under conditions of low soil S content, the percentage of bulbs in classes 3 and 4 increased with S dose to 47.5 kg ha^{-1} but decreased at higher doses. Plants properly nourished with S produce larger bulbs (Paula et al., 2002; Al-Fraihat, 2009; Kurtz and Ernani, 2010).

Bulb pungency

The quadratic polynomial equation for the maximum pungency at the dose of 70 kg S ha^{-1} required a significant adjustment (Fig 3). Significant adjustments were not required in the studies by Paula et al. (2002) and Lee et al. (2009), who found no increase in the pungency of onions with increasing S doses, probably due to the high S content of the soil, unlike our soil that contained only 4 mg S dm^{-3}. Pungency intensity is controlled by genetic and environmental factors, especially soil S content, temperature, and water availability (Randle and Bussard, 1993; Randle et al., 1997; McCallum et al., 2001). The addition of S for onion culture implies increased pungency to the genetically controlled limit, with differences between cultivars, above which pungency does not increase with increasing S doses. Yoo et al. (2006) and Grangeiro et al. (2008) stated that approximately 80% of the variation in the level of pungency in onions is explained by genetic factors.Taking into account the classification proposed by Miguel et al. (2004) and alliinase activity, pungency varied between 0.9 and 1.4 µmol g^{-1} pyruvic acid and was classified as very mild (0-2.9 µmol g^{-1}) with an extra-sweet flavour.

Soil analysis

S dose and evaluation period had significant interactions with soil pH and S-SO_4^{2-} content. The polynomial equations for soil pH did not require significant adjustments for values of 5.4, 5.5, 5.4, and 5.4 at S doses of 0, 15, 30, and 90 kg ha^{-1}, respectively (Fig 4). At doses of 45 and 60 kg ha^{-1} were observed adjustments quadratic polynomials, and soil pH increased until 45 and 57 days after sowing (DAS), respectively, but then decreased until 90 DAS (Fig 4). This initial increase in pH was likely due to the oxidation of elemental S, because heterotrophic microorganisms on the surface of particles containing elemental S produce thiosulphate ($S_2O_3^{2-}$), which, being acidic, reacts with H^+ ions, thereby increasing soil pH and leading to the formation of sulphite (SO_3^{2-}) (Germida and Janzen, 1993). According to these authors, other microorganisms are responsible for oxidising sulphides to sulphuric acid, which acidifies soil when dissociation forms sulphate (SO_4^{2-}) and releases H^+ ions. Our results corroborate those by Slaton et al. (2001), who observed the same effect on soil pH over time with the application of elemental S. The period of evaluation had no significant effect on pH at 30 and 90 DAS, with means of 5.5

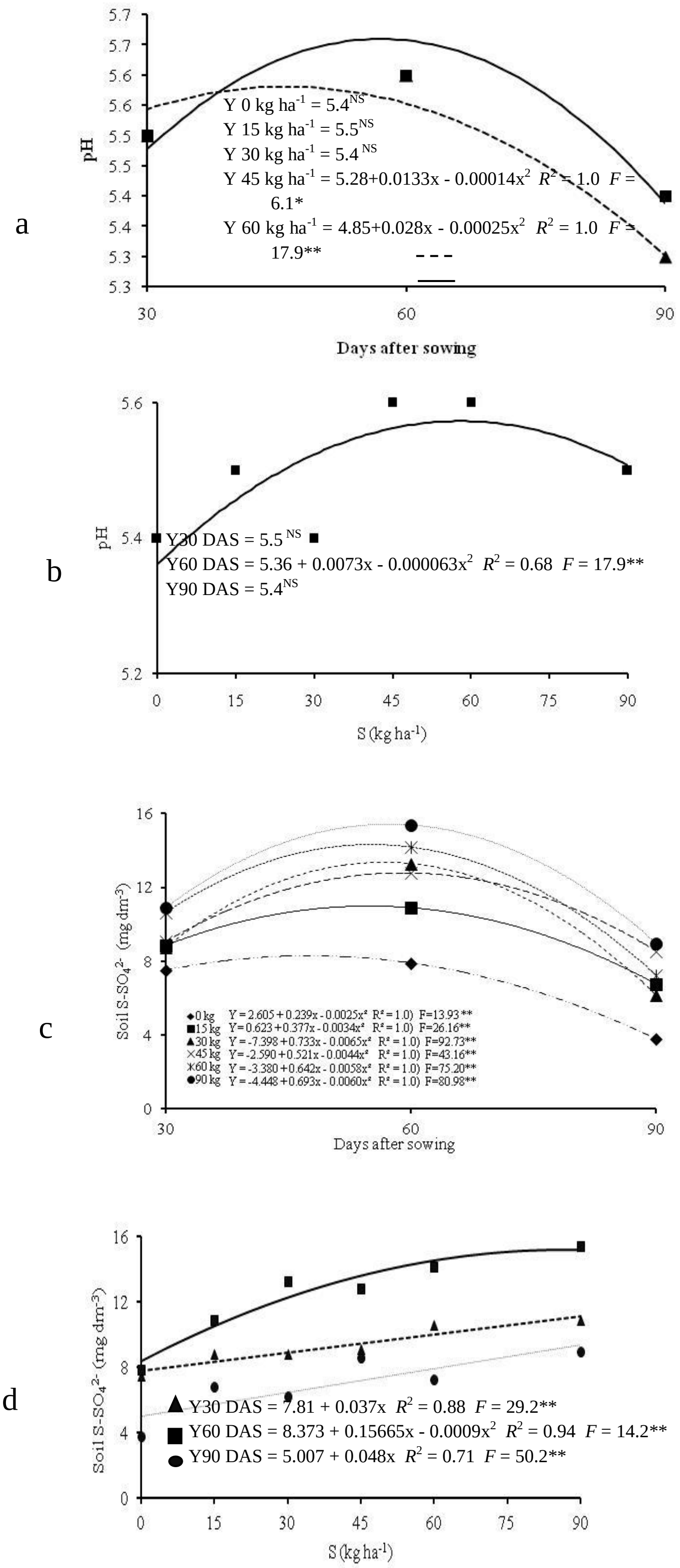

Fig 4. Soil pH (a, b) and $S\text{-}SO_4^{2-}$ (c, d) content as functions of the time of evaluation (30, 60, and 90 days after sowing and of the sulphur dose.

and 5.4, respectively (Fig 4). Microbial activity in soil remains low between 22 and 38 days of incubation of elemental S, oxidising only 12-15% of the total S applied (Horowitz and Meurer, 2006). Thus, 30 DAS may have been too short a period to significantly change pH. More than 90% of the elemental S, however, is oxidised by 90 DAS (Horowitz and Meurer, 2006). Other environmental factors of the soil and the crop itself may have interacted in a way to equalise pHs. The polynomial equation for 60 DAS required a significant adjustment. pH increased up to a dose of 58 kg S ha^{-1}, but higher doses decreased pH, to a low of 5.6 at 90 kg S ha^{-1} (Fig 4). The soil microorganisms responsible for elemental-S oxidation are highly active during this period, and higher doses of elemental S produce more thiosulphates that can react with H^+ ions and thereby produce the initial increase in pH (Horowitz and Meurer, 2006). High doses of elemental S can inhibit the activity of the microorganisms responsible for oxidation (Lawrence and Germida, 1988; Deng and Dick, 1990), that is, doses higher than 58 kg S ha^{-1} in our experiment may have been toxic to these microorganisms. The polynomial equations for soil S contents for the evaluated periods required significant adjustments for all treatments (Fig 4). Doses of 0, 15, 30, 45, 60, and 90 kg S ha^{-1} produced soil S contents of 8.3, 11.0, 13.4, 12.8, 14.3, and 15.4 mg dm^{-3} at 48, 55, 57, 59, 55, and 57 DAS, respectively. These results agreed with those obtained for soil pH. The period of increased microbial activity that oxidises elemental S is close to 60 days after incubation (Horowitz and Meurer, 2006). When S was applied to the soil, however, the soil $S\text{-}SO_4^{2-}$ contents were maximal between 55 and 59 DAS. During this period, 70-80% of the elemental S is oxidised to $S\text{-}SO_4^{2-}$ (Watkinson, 1989; Horowitz, 2003). Linear adjustments for soil $S\text{-}SO_4^{2-}$ content, depending on the S dose, were required for 30 and 90 DAS, because the soil $S\text{-}SO_4^{2-}$ content increased as the dose increased. A quadratic adjustment was required for 60 DAS with an increase in soil $S\text{-}SO_4^{2-}$ content to 87 kg S ha^{-1} (Fig 4). These results corroborated those by Paula et al. (2002). The S contents at 60 DAS were higher than those at 30 and 90 DAS, with the lowest values at 90 DAS (Fig 4). These results indicated that increasing doses of elemental S increased soil S contents. S content, however, tends to decrease over time due to the downward movement of S in the soil profile or to its uptake by the growing onion plants (Pôrto et al., 2006).

Materials and Methods

Experimental site

The experiment was conducted from 30 May to 10 October 2011 on the property of Santa Rita da Capela farm, in Jaboticabal, Brazil (21º18'10"S, 48º23'01"W; 610 m a.s.l.).

Soil and climatic characteristics

The soil (Red Latosol) has a very clayey texture, with 650 g kg^{-1} clay, 100 g kg^{-1} silt, 130 g kg^{-1} coarse sand, and 120 g kg^{-1} fine sand. The soil chemical parameters in the 0-0.20 m layer prior to the experiment were: pH($CaCl_2$), 5.6; H+aluminium, 26 $mmol_c$ dm^{-3}; organic matter, 16 g dm^{-3}; Ca, 17 $mmol_c$ dm^{-3}; Mg, 6 $mmol_c$ dm^{-3}; P(resin), 53 mg dm^{-3}; K, 1.6 $mmol_c$ dm^{-3}; cation-exchange capacity, 53.6 $mmol_c$ dm^{-3}; base soil saturation, 52%; boron, 0.14 mg dm^{-3}; copper, 3.9 mg dm^{-3}; iron, 13 mg dm^{-3}; manganese, 19.9 mg dm^{-3}; zinc, 3.0 mg dm^{-3}; aluminium, 0 mg dm^{-3}; and $S\text{-}SO_4^{2-}$, 4.0 mg dm^{-3}.

The S content is considered low relative to those recommended by Raij et al. (1997). The mean maximum and minimum temperatures during the experimental period were 29.4 and 13.9 ºC respectively, with an average of 20.6 ºC. The average relative humidity of the air was 59.1%, and rainfall was 53.4 mm.

Experimental design

The experiment had a randomised complete-block design with four replicates of six treatments of S doses (0, 15, 30, 45, 60, and 90 kg S ha^{-1}). The experimental plots were 1.8 m wide and 2.5 m long with four double rows of plants. The plant parameters were evaluated for the plants from the two central double rows, excluding the plants 0.5 m from each end of the rows.

Planting, management practices, and harvesting

Soil preparation consisted of ploughing, harrowing, application of 1.5 t ha^{-1} gross magnesium thermophosphate (no S), and formation of seedbeds with a tractor-drawn machine. At planting, 1.2 t ha^{-1} of fertiliser containing 4% N, 14% P_2O_5, and 8% K_2O was applied. The sources of N, P, and K were ammonium nitrate, triple superphosphate, and potassium chloride, respectively, and a concentrate of calcium and magnesium (filler) was used to balance the formula NPK fertilizer, avoiding the application of S in the planting. The elemental S (S^0)used in the experiment was Sulfurgran® (Produquímica, Brazil), which contains 90% S^0, and was applied five days after seeding. The 'Perfecta' onions were directly sown on 30 May 2011. The rows of the double rows were 0.15 m apart, and the double rows were 0.25 m apart. Plants within a row were spaced at 0.06 m. Fertiliser was broadcast 25 and 50 DAS at 25 kg ha^{-1} of N and K_2O from urea and potassium chloride, respectively. The plots were irrigated and sprayed with recommended insecticides and fungicides using a central-pivot system according to the stage of crop development (Abreu et al., 1980). Plant samples were collected on 10 October 2011 when 70% of the plants in the collection area of each plot approached senescence or when the pseudostems began to wilt and fell.

Characteristics evaluated

a) Plant development: height (cm), leaf number, and DML (g m^{-2}) were evaluated 90 DAS. The bulbs were well formed by 120 DAS, and the diameter (mm) and length (mm) of the bulbs were measured.
b) Leaf analysis: the concentrations of macronutrients (g kg^{-1}) in the leaves 90 DAS (early bulbification) were determined for the diagnosis of nutritional status according to Raij et al. (1997).
c) Productivity (t ha^{-1}): the bulbs harvested from the collection areas of the plots were weighed to estimate crop productivity.
d) Bulb production in classes 3 and 4 (% of productivity): the equatorial bulb diameters (CEAGESP, 2001) for classes 3 (50.1-70 mm) and 4 (70.1-90 mm) bulbs were measured and quantified as proportions of the total productivity.
e) Bulb pungency: pungency was evaluated by alliinase activity as described by Schwimmer and Weston (1961), and the classification of pungency and flavour followed the system by Miguel et al. (2004).
f) Soil analysis: Soil samples were collected from the 0-0.20 m layer 30, 60, and 90 DAS at eight random points in each plot, and the pH($CaCl_2$) and S-SO_4^{-2} content were analysed as described by Raij et al. (2001).

Data analysis

The analysis of variance used *F*-tests, and polynomial regression was performed to determine the equations that best fit the data with the highest levels of significance and highest coefficients of determination. The analyses of soil pH and S content followed a split-plot design, with plots and subplots corresponding to S doses (0, 15, 30, 45, 60, and 90 kg ha^{-1}) and evaluation periods (30, 60, and 90 DAS), respectively. The other characteristics were evaluated as a randomised block design with six treatments corresponding to the S doses. The analyses of variance were performed using SAS version 9.2 (SAS Institute, Cary, USA).

Conclusions

Bulb pungency increased with S dose.

Supplying 45 kg S ha^{-1} to soil with a low nutrient content promoted maximum productivity of 'Perfecta' onions.
'Perfecta' onions produced very mildly pungent bulbs with an extra-sweet flavour in soil with a low nutrient content and fertilised with up to 90 kg S ha^{-1}. The supply of elemental S to the soil caused a slight early increase in pH, which tended to decrease over time. The availability of S-SO_4^{2-} in the soil increased with the supply of elemental S.

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