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RESEARCH ARTICLE

Physical and physicochemical characteristics of tomato fruits grown under different irrigation water levels and phosphorus sources and rates

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ABSTRACT

Phosphorus (P) is one of the most limiting nutrients for growth and development of crops, and is important for soil fertility managements, since it affects the quality of fruits. With the hypothesis that different levels of irrigation and phosphorus fertilization interfere in the physical and physicochemical properties of tomatoes, the objective of this experiment was to verify this hypothesis and analyze the behavior of the fruits' responses. The experiment was conducted in a greenhouse at the Hydraulic and Irrigation Laboratory of the Federal Institute of Education, Science, and Technology of the State of Goiás, in Rio Verde, Goiás, Brazil. A randomized block design was used, with a 4 × 2 × 4 split-plot arrangement and three replications, totaling 96 experimental plots. The treatments consisted of four P_2O_5 rates: 25%, 50%, 100%, and 200% of the recommended rate; two P sources: monoammonium phosphate (MAP) and organo-mineral (OM); and four IWL: 50%, 75%, 100%, and 125% of the field capacity. The fruits were evaluated for longitudinal (FLD) and transversal (FTD) diameters, potential hydrogen (pH), titratable acidity (TA), total soluble solid (TSS) contents, and TSS to TA ratio (TSS/TA). The effect of the interactions between the factors IWL and P rate, IWL and P source, and P rate and source were significant for FLD and FTD, TSS, TA, and TSS/TA. The effects of the interactions between IWL and P rate, and IWL and P source were significant for pH. The MAP source combined with the rate of 25% and IWL of 125% resulted in tomato fruits with larger FLD and FTD. The rate of 25% combined with IWL of 77% and 100% resulted in tomato fruits with higher TSS and pH. The OM source resulted in tomato fruits with higher TA when combined with IWL of 50%, and larger FLD when combined with IWL of 105% and 125%.

Keywords: *Solanum lycopersicum* L.; phosphate fertilizer application; organo-mineral fertilizer; localized irrigation; fruit quality.

INTRODUCTION

Tomato (*Solanum lycopersycum* L., Solanaceae) has a socioeconomic and nutritional importance because it is one of the most grown and consumed agricultural products in the world, which is consumed fresh and as processed products, such as extracts and sauces (Adigun et al., 2018; Akhtar et al., 2019; Arab et al., 2019). In addition, the tomato plant, due to its good acceptance and high consumption, can be cultivated throughout the year in open fields, vegetable gardens and agricultural greenhouses and guarantees employment and income for small and medium farmers (Berni et al., 2018; Lopes Sobrinho et al., 2022).

According to data obtained by the Brazilian Institute of Geography and Statistics (IBGE), world tomato production was estimated at 4.0 million tons, with growth of 2.0% in relation to the last survey. In Brazil, the planted area corresponds to 56,874 hectares, forecast to increase by 2.2% and the largest national producers are Goiás and São Paulo, with 28.9% and 25.6%, respectively, of national production. The average productivity in the State of Goiás was estimated at 92,394 kg/ha^{-1} and São Paulo at 78,344 kg/ha^{-1} (IBGE, 2021).

The consumption of tomato contributes to the ingestion of compounds essential for human health such as antioxidants that are responsible for eliminating free radicals and

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reducing cell damage, fibers and minerals (Avio et al., 2018; Ilahy et al., 2018). Due to their properties of bioactive compounds such as lycopene, phenolic compounds and vitamins contribute to the promotion and maintenance of human health, reducing the incidence of cancers and cardiovascular diseases, as tomato plants contain high concentrations of antioxidant molecules (carotenoids and lycopene) (Ding et al., 2016; Stinco et al., 2016; Kelebek et al., 2017; Barba et al., 2017; Barros et al., 2017; Wen et al., 2017; Liu et al., 2018).

The management of soil or substrate fertility for tomato crops is important for the maintenance of fruit yield and quality, since tomato is one of the vegetables with the highest nutrient demand (Du et al., 2017). Phosphorus (P) is among the essential nutrients for tomato production, and is the primary macronutrient absorbed in lower quantity when compared to nitrogen and potassium. P is mostly absorbed by plants (80% to 90%) as dihydrogen phosphate ($H_2PO_4^-$) and disodium phosphate (Na_2HPO_4); it is mobile in plant tissues and responsible for enzymatic metabolic processes, and participates in plant cell division, photosynthesis, and respiration (Shabnam and Iqbal, 2016).

P is responsible for playing an important role in plant growth and metabolism. Due to its low mobility, soil P limits plant growth. Overcoming its deficiency and increasing availability is an essential issue to achieve high crop yields, highlighting the need to apply large amounts of inorganic phosphate fertilizers in agricultural ecosystems (Menezes et al., 2018; Zhu et al., 2018; Higo et al., 2020).

The analysis of the tomato nutritional status requires the evaluation of fruit aspects, such as size, shape, and peel color; nutritional value; and flavor, which is related to contents of total soluble solid, vitamin C, minerals, lycopene, xanthophylls, beta-carotene, and total carotenoids, °Brix, potential hydrogen (pH), and titratable acidity (Ding et al., 2016; Du et al., 2017). Thus, studies evaluating physicochemical and nutritional characteristics of fruits are essential to acquire quantitative and qualitative information that assist in add value and promote the tomato consumer market (Silva et al., 2015; Chaves Neto, 2019).

Studies have analyzed fruit quality characteristics, but they are incipient regarding the effect of sources and rates of phosphorus and irrigation water levels on fruit quality. With the hypothesis that different levels of irrigation and phosphorus fertilization interfere in the physical and physicochemical properties of tomatoes, the objective of this experiment was to verify this hypothesis and analyze the behavior of the fruits' responses.

MATERIAL AND METHODS

The experiment was conducted in a greenhouse at the Hydraulic and Irrigation Laboratory of the Federal Institute of Education, Science, and Technology of the State of Goiás, Brazil, in Rio Verde, Goiás, Brazil (17°48'28"S, 50°53'57"W, and 720 m of altitude).

A digital thermohygrometer was placed at 1.5 m height in the central point of the greenhouse to obtain the mean air temperatures (°C) and relative humidity (%) during the tomato crop cycle; the results were, respectively, 25.77 °C and 51.71% (September 2019), 25.36 °C and 61.41% (October 2019), and 24.22 °C and 71.33% (November 2019).

The soil used was classified as a clayey, dystrophic Typic Hapludox of the Cerrado Biome (Latossolo Vermelho distroferrico - LVdf, according to the Brazilian Soils Classification System (Santos et al., 2018). Soil samples were collected from the 0.0-0.20 m layer for evaluations; then, 23 kg of soil (density = 1.3 g cm^{-3}) were added to 25-liter plastic pots, which were placed inside the greenhouse.

A randomized block design was used, with a 4×2×4 split-plot arrangement, consisted of four irrigation water levels (IWL) (50%, 75%, 100%, and 125% of the field capacity) in the plots, two P_2O_5 sources in the subplots (monoammonium phosphate – MAP; and organo-mineral fertilizer - OM), and four P rates in the sub-subplots (25%, 50%, 100%, and 200% of the recommended rate). The experiment was conducted with three replications, totaling 96 experimental plots.

The P rates per pot were defined based on the number of plants, considering a population of 20,000 plants per hectare. The soil P fertilizers were applied based on results of the soil chemical analyses, considering different percentages of the recommended rate proposed by Sousa and Lobato (2004) for tomato crops. The P rates applied were 25%, using 0.02885 kg ha^{-1} of MAP, 0.03248 kg ha^{-1} of OM, or 0.00075 kg ha^{-1} of P_2O_5; 50%, using 0.0577 kg ha^{-1} of MAP, 0.06486 kg ha^{-1} of OM, or 0.0015 kg ha^{-1} of P_2O_5; 100%, using 0.1154 kg ha^{-1} of MAP, 0.12976 kg ha^{-1} of OM, or 0.003 kg ha^{-1} of P_2O_5; and 200%, using 0.2308 kg ha^{-1} of MAP, 0.25952 kg ha^{-1} of OM, or 6.00 kg ha^{-1} of P_2O_5, which were split into two applications.

The table tomato cultivar used (*Solanum lycopersicum* L. cv. Gaúcho Melhorado Nova Seleção) belongs to the Salad group, which presents indeterminate growth habit. The seedlings were transplanted when they presented three to four true leaves, using the spacing recommended for the crop: 1.00 m between rows and 0.50 m between plants.

The plants were grown in a trellising system with plastic rope (Fig. 1), as recommended by Becker et al. (2016). The crop management and cultural practices were carried out according to recommendations of Silva and Valley (2007) and Clemente and Boiteux (2012) for tomato crops.

Fig 1. Overview of the experiment with tomato culture in a staking with ribbon in an agricultural greenhouse of the Federal Institute of Education, Science and Goiás Technology in Rio Verde, Goiás, 2019.

The soil water retention was determined through the soil water retention curve was using the equation of van Genuchten (1980). A surface drip irrigation system was used, which was managed using digital tensiometers and the performance of the irrigation system was evaluated based on the classification of Mantovani (2001) by the water distribution uniformity tests.

The fruits were evaluated for physical characteristics: fruit longitudinal diameter (FLD) and fruit transversal diameter (FTD); and physicochemical characteristics: potential hydrogen (pH), titratable acidity (TA), total soluble solid (TSS) contents and TSS to TA ratio (TSS/TA). FLD and FTD were determined using a digital caliper (Starrett® EC799), and the results were expressed in millimeters.

Physicochemical characteristics were evaluated using pulp samples from tomato fruits processed in a blender. Five fruits were randomly chosen to form a representative homogeneous sample of each treatment. The pH was determined directly from the tomato juice, using a portable digital pH-meter (Tecnopon®). TSS were evaluated using five fruits homogenized in a blender for three minutes; the readings were carried out using a refractometer (A. KRÜSS Optronic®) (Fig. 2) (Instituto Adolfo Lutz, 2008).

Fig 2. A.KRÜSS Optronic® refractometer used to obtain the ºBrix for the tomato crop grown in a greenhouse at the Federal Institute of Education, Science and Technology Goiano, Rio Verde, Goiás, 2019.

TA was determined by titration, using NaOH at 0.1 N, as described by the Association of Official Agricultural Chemists (Fig. 3) (AOAC, 2000). TSS/TA was estimated by dividing the TSS by the TA.

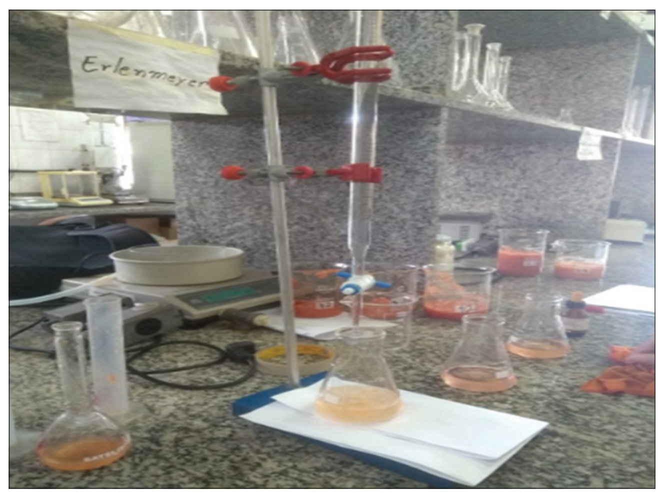

Fig 3. Titration used to obtain the titratable acidity (TA) of the tomato crop grown in a greenhouse at the Federal Institute of Education, Science and Technology of Goiás, Rio Verde, Goiás, 2019.

The data were subjected to analysis of variance (ANOVA) by the F test at 5% probability level; significant means found for P rates and irrigation water levels were subjected to regression analysis; significant means found for the effect of phosphorus sources were compared by the Tukey's test (p<0.05), using the statistical program SISVAR® (Ferreira, 2011).

RESULTS AND DISCUSSION

The analysis of variance showed that the effect of the interactions between irrigation water level (IWL) and P rate, IWL and P source, and P rate and P source were significant for fruit longitudinal diameter (FLD), fruit transversal diameter (FTD), and total soluble solid contents (TSS), titratable acidity (TA), and TSS to TA ratio (TSS/TA) in tomato fruits. In addition, the effect of the interactions between IWL and P rate, and IWL and P source was significant for potential hydrogen (pH).

The P rate of 25% of the recommended rate resulted in the largest FLD when using the IWL of 125%, estimated in 24.17 mm with a linear fit of the data (Fig. 4A). The P rate of 50% showed the largest estimated FLD (24.19 mm) for the IWL of 96%, and the lowest (18.63 mm) for the IWL of 50%, estimated with a quadratic fit of the data (Fig. 4B). The P rate of 100% showed the largest FLD (25.92 mm) for the IWL of 125%, and the lowest (19.39 mm) for the IWL of 73%, estimated with a quadratic fit of the data (Fig. 4C). The rate of 200% showed the largest FLD (19.61 mm) for the IWL of 125%, and the lowest (16.09 mm) for the IWL of 86%, estimated with a quadratic fit of the data (Fig. 4D).

The IWL of 100% showed the largest estimated FLD (21.98 mm) for the P rate of 152%, and the lowest (14.03 mm) for the P rate of 25%, estimated with a quadratic fit of the data (Fig. 4E). The IWL of 75% showed the largest FLD (22.67 mm) for the P rate of 25%, estimated with a linear fit of the data (Fig. 4F). The IWL of 100% showed the largest FLD (24.25 mm) for the P rate of 200%, estimated with a linear fit of the data (Fig. 4G).

Fruit growth is affected by the water status (Soares et al., 2011), thus, decreases in fruit growth and size are connected to daily increases or decreases in plant water potential and soil water contents. When receiving organomineral fertilization, tomato plants grow more, ensuring a better nutritional balance in their tissues and favoring the transport of photoassimilates, water and nutrients, which improves fruit quality (Almeida et al., 2019; Peres et al., 2020).

Pinto (2017) evaluated the effect of different P rates and application methods in tomato crops and found no significant effect on TSS, TA, FLD, and FTD. Thus, tomato fruit quality is affected by biotic factors (vegetative propagation, seed dispersion, intra and interspecific interaction, and developmental stages) and abiotic factors (temperature, light, soil, nutrient availability, and water deficit) (Melo et al., 2004; Loos et al., 2009). Plants grown in environments under water stress present low cell division rate, turgidity pressure, and stretching due to decreases in water content (Taiz et al., 2017).

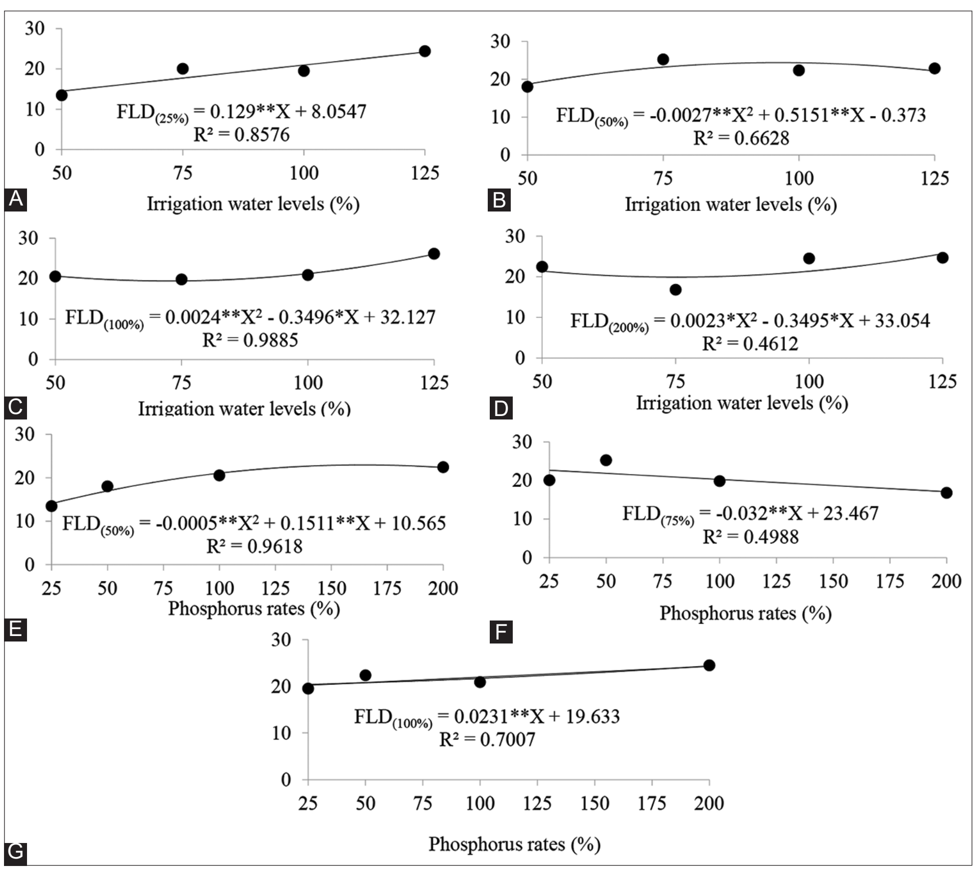

Fig 4. Longitudinal diameter (FLD) of tomato fruits as a function of irrigation water levels (IWL) (A, B, C, and D) and phosphorus rates (E, F, and G).

The lowest tomato fruits diameters found for IWL lower than 100% were connected to the water deficit, which affects plant photosynthetic processes and fruit yield. These results confirm those of Silva et al. (2013), who evaluated the effect of different irrigation water levels on the agronomic performance of tomato plants and found linear increases in FLD and FTD as the IWL was increased, with increases of 55.22% and 57.64%, respectively, when increasing the IWL from 33% to 166% of the crop evapotranspiration.

The IWL of 125% showed the largest FLD (25.30 mm) for the OM source, estimated with a linear fit of the data. The IWL with the MAP source showed no significant difference in FLD (Fig. 5A). The effect of the P source was significant for FLD when combined with the IWL of 50% and 75%, presenting the largest FLD for the MAP source, and increases of 33.70% for the OM source and 25.93% for the MAP source. Contrastingly, the IWL of 125% showed the largest FLD for the OM source, with an increase of 8.54% (Fig. 5B).

In tomato production, as it is a well-known key nutrient, P in the soil aims to maximize plant growth and development with evidence of adequate levels. However, the effect of different amounts of phosphate fertilizers on tomato agronomic performance is still unknown, and investigations into the adjustment of phosphate fertilization levels due to the correct choice of doses and sources are important (Zhu et al., 2018; Higo et al., 2020; Lopes Sobrinho et al., 2022).

The P rate of 200% showed the largest estimated FLD (36.33 mm) for the OM source, and the lowest (17.39 mm) for the rate of 25% (Fig. 6A). The phosphorus rates using the MAP source showed no significant difference in FLD. The effect of the P source on FLD was significant at rates of 25% and 50%, with larger FLD for the MAP source, with increases of 27.72% and 20.57%, respectively (Fig. 6B).

The P rate of 100% showed the largest estimated FTD (16.57 mm) for the IWL of 97%, and the lowest (9.82 mm) for the IWL of 50%, estimated with a quadratic fit of the data (Fig. 7A). Koetz et al. (2010) evaluated agronomic characteristics of tomato plants under different IWL and found the largest FTD for the IWL of 125% of the evapotranspiration, and they also found that increases in IWL increase fruit diameter.

The P rate of 50% showed the largest estimated FTD (18.18 mm) for the IWL of 93%, and the lowest (14.98 mm) for the IWL of 50%, estimated with a quadratic fit of the data (Fig. 7B). Similar studies were conducted by Soares et al. (2013), and Candido et al. (2015), who evaluated the production performance and fruit quality of tomato plants subjected to different irrigation water levels and found decreases in FTD as the IWL was decreased.

The P rate of 100% showed the largest estimated FTD (19.16 mm) for the IWL of 106%, and the lowest (13.61 mm) for the IWL of 50%, estimated with a quadratic fit of the data (Fig. 7C). The P rate of 200% showed the largest estimated FTD (19.79 mm) for the IWL of 125%, and the lowest (13.02 mm) for the IWL of 72%, estimated with a quadratic fit of the data (Fig. 7D).

The IWL of 50% showed the largest estimated FTD (16.78 mm) for the P rate of 171%, and the lowest

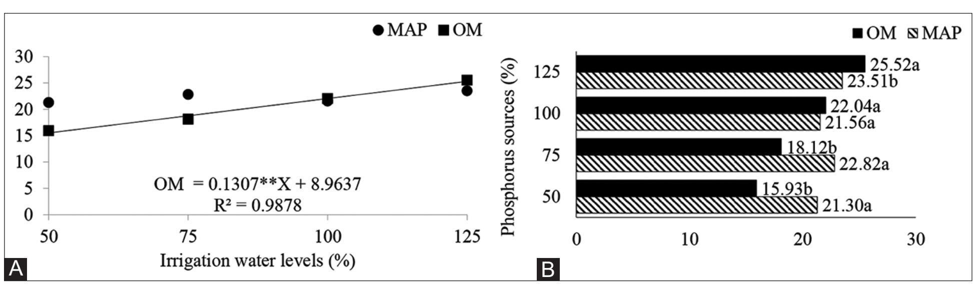

Fig 5. Longitudinal diameter (FLD) of tomato fruits as a function of irrigation water levels (IWL) (A) and phosphorus sources (B).

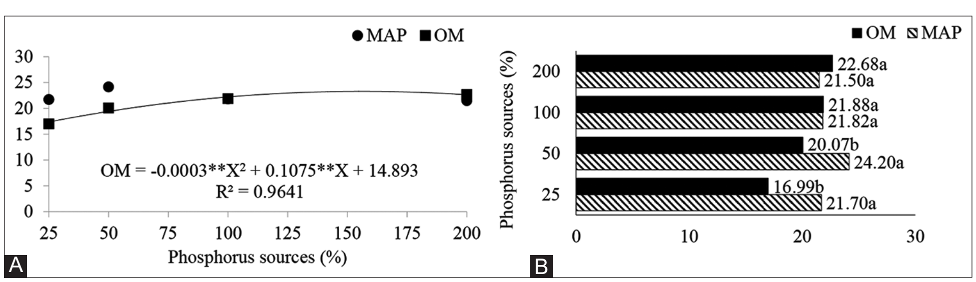

Fig 6. Longitudinal diameter (FLD) of tomato fruits as a function of rates (A) and sources (B) of phosphorus.

(10.35 mm) for the P rate of 25%, estimated with a quadratic fit of the data (Fig. 7E). The IWL of 75% showed the largest estimated FTD (19.57 mm) for the P rate of 25%, and the lowest (11.05 mm) for the P rate of 25% (Fig. 7F). The IWL of 100% showed the largest estimated FTD (19.91 mm) for the P rate of 130%, and the lowest (14.35 mm) for the P rate of 25%, estimated with a quadratic fit of the data (Fig. 7G). The IWL of 125% showed the largest FTD (18.62 mm) for the P rate of 200%, estimated with a linear fit of the data (Fig. 7H).

The largest FTD was found for the IWL of 125%, estimated in 18.14 mm for the MAP source, which was larger than that found for the OM source, with linear fit of the data. The OM source showed the largest FTD for the IWL of 105%, estimated in 16.71 mm, and the lowest (10.09 mm) for the IWL of 50%, estimated with a quadratic fit of the data (Fig. 8A). The interaction between the factors was significant for FTD in the IWL of 50%, 75%, and 125%, with the MAP source showing larger FTD than the OM source, presenting increases of 55.50%, 18.81%, and 14.19%, respectively (Fig. 8B).

The P rate of 25% resulted in a larger estimated FTD (18.34 mm) for the MAP source when compared to the OM source, and a P rate of 124% resulted in the lowest FTD (16.38 mm), estimated with a quadratic fit of the data. The IWL with the MAP source showed no significant difference in FLD (Fig. 9A). The interaction between the factors was significant in the P rates of 25%, 50%, and 200%; the MAP source showed a larger FTD than the OM source, with increases of 62.78%, 22.17%, and 19.44%, respectively (Fig. 9B). Contrastingly, the P rate of 100% showed larger FTD for the OM source, with an increase of 23.28% (Fig. 9B).

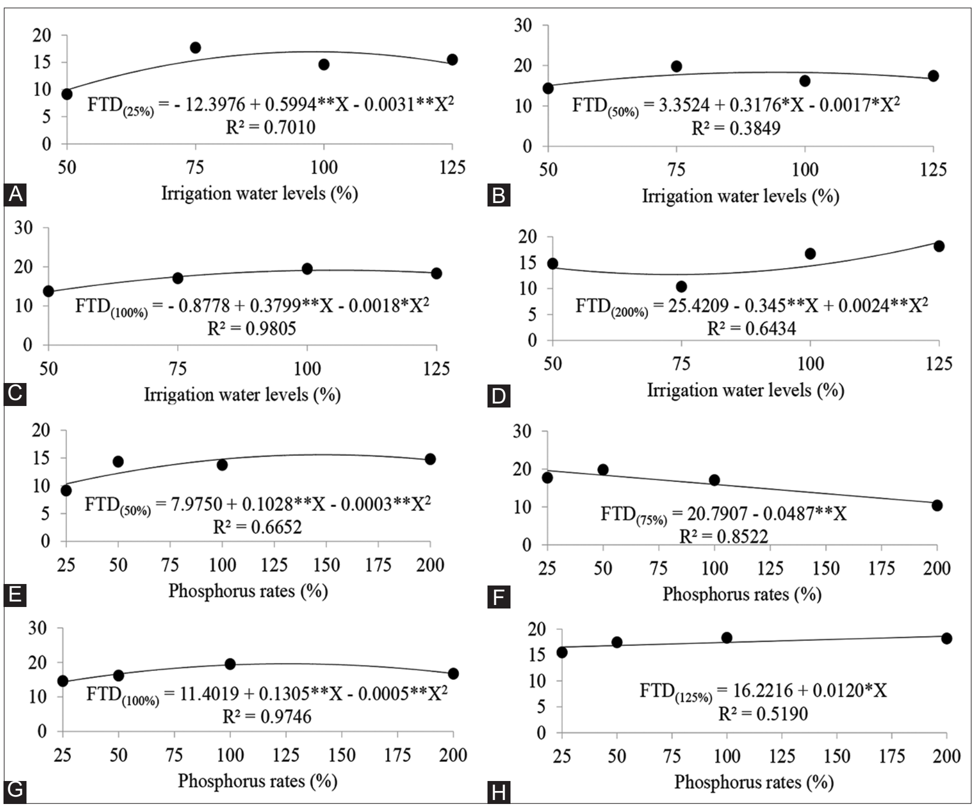

Fig 7. Transversal diameter (FTD) of tomato fruits as a function of irrigation water levels (IWL) (A, B, C, and D) and phosphorus rates (E, F, G, and H).

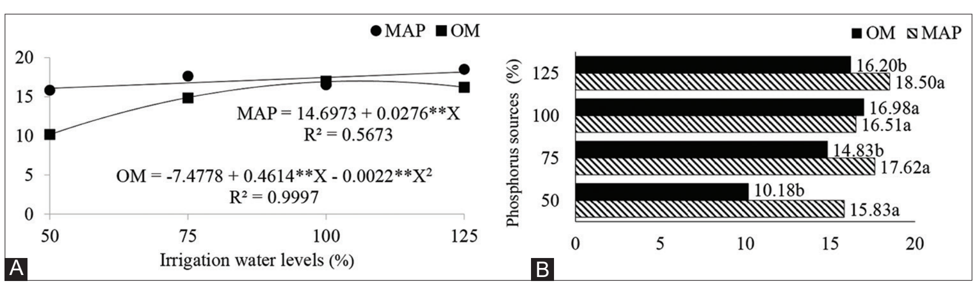

Fig 8. Transversal diameter (FTD) of tomato fruits as a function of irrigation water levels (IWL) (A) and phosphorus sources (B).

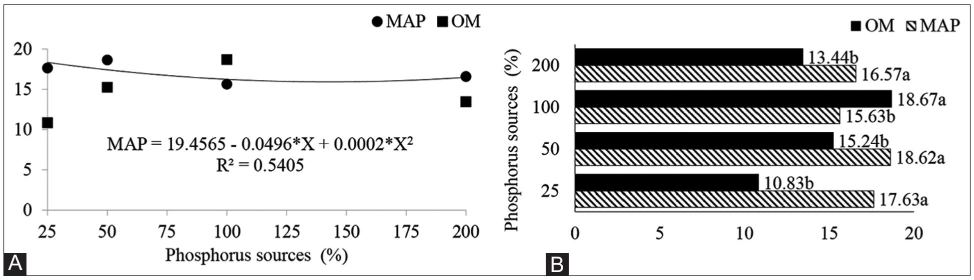

Fig 9. Transversal diameter (FTD) of tomato fruits as a function of rates (A) and sources (B) of phosphorus.

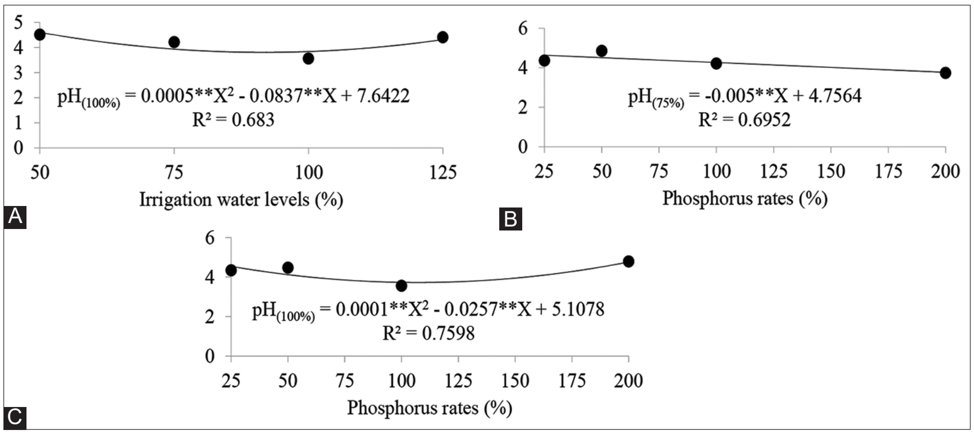

Fig 10. Potential hydrogen (pH) of tomato fruits as a function of irrigation water levels (IWL) (A) and phosphorus rates (B and C).

Vidal et al. (2017) evaluated the response of tomato plants to applications of different soil fertilizers and found that the use of mineral fertilizer resulted in the largest FTD, and the use of organic fertilizer resulted in the largest FLD. Thus, the presence of organic matter with mineral nutrients in organomineral fertilizers promotes the absorption and helps in the transport of photoassimilates produced by the plant itself (Almeida et al., 2019). The slow release of nutrients occurs in organominerals, which tends to persist for a longer period in the soil (Aguilar et al., 2019; Souza et al., 2020).

The rate of 100% showed the highest estimated pH (4.99) for the IWL of 125%, and the lowest (4.13) for the IWL of 84%, estimated with a quadratic fit of the data (Fig. 10A). The IWL of 75% showed the highest pH (4.63) for the P rate of 25%, estimated with a linear fit of the data (Fig. 10B). The IWL of 100% showed the highest estimated pH (4.520 for the P rate of 25%, and the lowest (3.45) for the rate of 128%, estimated with a quadratic fit of the data (Fig. 10C).

Martins et al. (2018) evaluated physical and physicochemical characteristics of tomato fruits as a function of P rates and found significant effect of P rates on pH, but the lowest rates showed a quadratic fit of the data. Moreover, Soares et al. (2012) evaluated tomato fruit quality under different IWL and found increases in pH as the IWL was increased.

The IWL of 50% showed the highest estimated pH (4.38) for the MAP source, and the lowest (3.68) for the IWL of 98%, estimated with a quadratic fit of the data. The IWL with the OM source showed no significant difference in pH (Fig. 11A). The interaction between the factors was significant in the IWL of 75% and 100%, with a higher pH for the OM when compared to the MAP source, presenting increases of 11.57% and 18.62%, respectively (Fig. 11B).

The value of pH is important for the acceptance of a food product in the consumer market, since a pH lower than 4.5 is desirable to prevent the proliferation of microorganisms (Monteiro et al., 2008). Thus, excess acid fruits are not desirable by consumers. The ideal pH for tomatoes is higher than 3.7 (Silva and Giordano, 2000; Borguini, 2002).

Similarly, Santiago et al. (2018) evaluated the effect of different IWL on tomato fruit quality and found that the higher the IWL, the lower the fruit acid contents, thus, the better the flavor. Araújo et al. (2018) evaluated five rates of phosphate soil fertilizer and found fruit pH values of 4.56 to 4.5 from the lowest to the highest P rate; In addition, they found TA between 0.80% and 0.87%, and °Brix between 4.41 and 4.75.

The P rate of 25% showed the highest estimated TSS (4.30 °Brix) for the IWL of 77%, and the lowest (3.40 °Brix) for the IWL of 125%, estimated with a quadratic fit of the

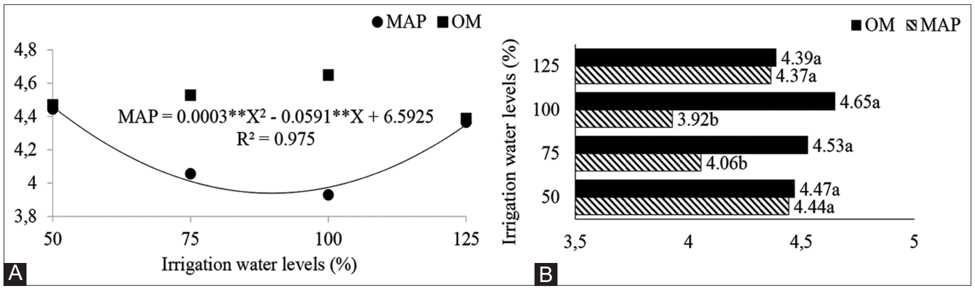

Fig 11. Potential hydrogen (pH) of tomato fruits as a function of irrigation water levels (IWL) (A) and phosphorus sources (B).

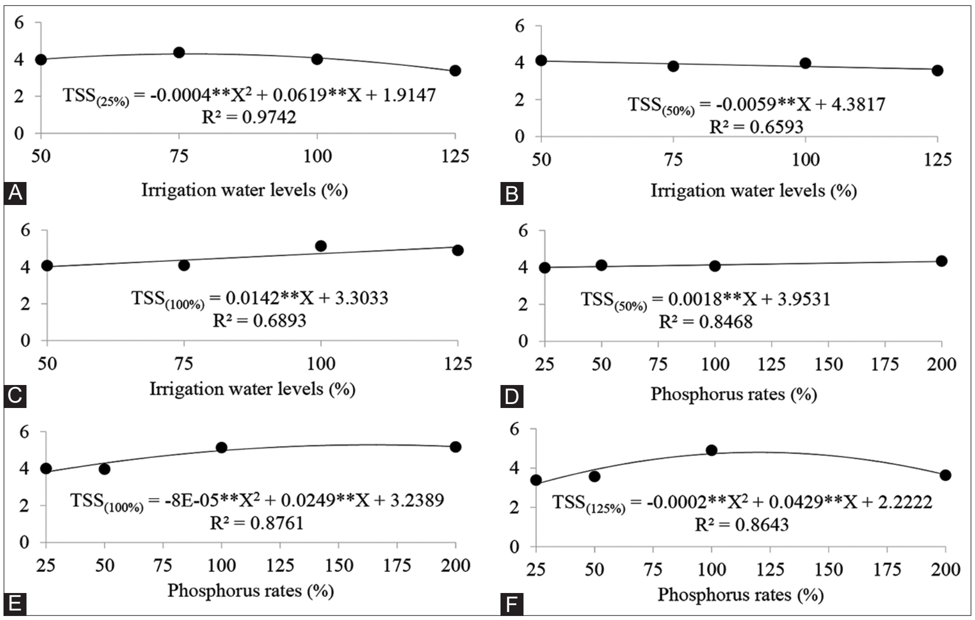

Fig 12. Total soluble solid contents (TSS) of tomato fruits as a function of irrigation water levels (IWL) (A, B and C) and phosphorus rates (D, E, and F).

data (Fig. 12A). The rate of 50% showed the highest TSS for the IWL of 50%, estimated in 4.08 °Brix with a linear fit of the data (Fig. 12B). The rate of 100% showed the highest TSS for the IWL of 125%, estimated in 5.07 °Brix with a linear fit of the data (Fig. 12C).

The IWL of 50% showed the highest estimated TSS (4.31 °Brix) for the rate of 200% (Fig. 12D). The IWL of 100% showed the highest estimated TSS (8.23 °Brix) for the rate of 200%, and the lowest (3.86 °Brix) for the rate of 25%, estimated with a quadratic fit of the data (Fig. 12E). The IWL of 125% showed the highest estimated TSS (4.52 °Brix) for the rate of 107%, and the lowest (2.80 °Brix) for the rate of 200%, estimated with a quadratic fit of the data (Fig. 12F).

The IWL of 94% showed the highest estimated TSS (4.55 °Brix) for the MAP source, and the lowest for the IWL of 50%, estimated in 4.35 °Brix with a quadratic fit of the data. The OM source showed the highest estimated TSS (4.30 °Brix) for the IWL of 87%, and the lowest (3.71 °Brix) for the IWL of 125% (Fig. 13A). The effect on the IWL of 100% and 125% with OM source was significantly higher than that with the MAP source, with increases in TSS of 9.88% and 8.62%, respectively (Fig. 13B). The TSS also showed significant differences with the IWL of 50%, however, the highest values were found for the MAP source.

Santiago et al. (2018) evaluated the quality of cherry tomatoes grown under different IWL and found no significant difference in TSS. Marouelli and Silva (2006) evaluated tomato crops grown under different IWL during the fruiting stage and found no significant effect on TSS. Irrigation with water deficit during the physiological maturation stage is an alternative to increase TSS and decrease yield losses (Johnstone et al., 2005).

The highest TSS for the MAP source was found with the rate of 200%, estimated in 4.30 °Brix with a linear fit of the data, but it was lower than that found for the OM source. The OM source showed the highest TSS (4.84 °Brix) for rate of 134%, and the lowest (3.66 °Brix) for the rate of 25%, estimated with a quadratic fit of the

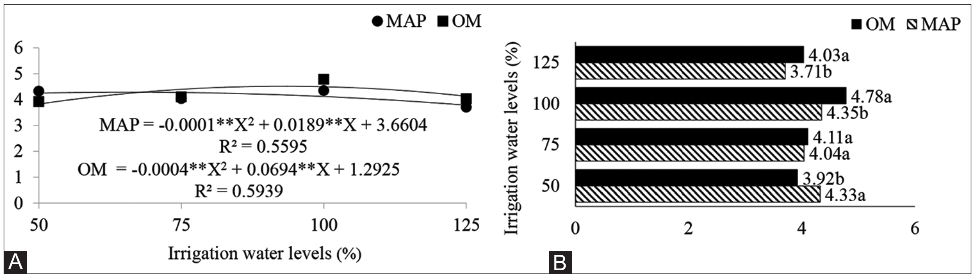

Fig 13. Total soluble solid contents (TSS) of tomato fruits as a function of irrigation water levels (IWL) (A) and phosphorus sources (B).

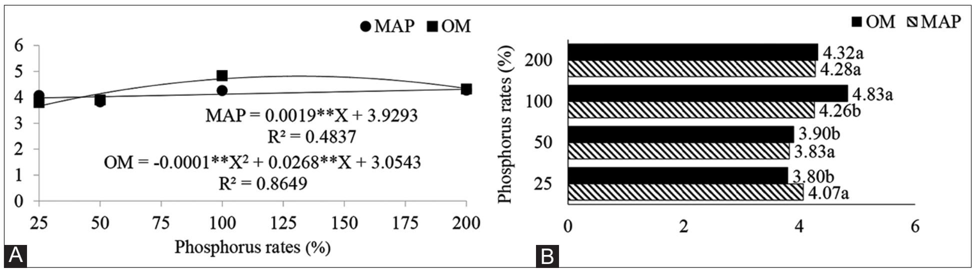

Fig 14. Total soluble solid contents (TSS) of tomato fruits as a function of rates (A) and sources (B) of phosphorus.

data (Fig. 14A). The interaction between the factors was significant for TSS in the P rates of 50% and 100%, with the OM source showing higher TSS than the MAP source, presenting increases of 1.82% and 13.38%, respectively. Contrastingly, considering the rate of 25%, the MAP source showed higher TSS than the OM source, with an increase of 7.10% (Fig. 14B).

TSS is affected by several environmental and intrinsic factors, such as crop location, harvest time, air temperature, nutrient absorption capacity, maturation stage at harvest, and cultural practices (Silva et al., 1994; Nascimento et al., 2013). In addition, it promotes the flavor of the fruits and affects the choice of consumers and industrial yields (Silva and Giordano, 2000) because it comprises sugars and acids that are indicators of fruit quality (Guimarães et al., 2008).

The P rate of 25% showed the highest TA for the IWL of 50%, estimated in 0.39% with a linear fit of the data (Fig. 15A). The rate of 50% showed the highest estimated TA (0.36%) for the IWL of 50%, and the lowest (0.21%) for the IWL of 80%, estimated with a quadratic fit of the data (Fig. 15B). The rate of 200% showed the highest estimated TA (0.34%) for the IWL of 50%, and the lowest for the IWL of 85%, estimated in 0.26% with a quadratic fit of the data (Fig. 15C).

The IWL of 50% showed the highest estimated TA (0.91%) for the P rate of 200%, and the lowest (0.39%) for the rate of 25%, estimated with a quadratic fit of the data (Fig. 15D). The IWL of 75% showed the highest estimated TA (0.31%) for the rate of 25%, and the lowest (0.25%) for the rate of 120%, estimated with a quadratic fit of the data (Fig. 15E). The IWL of 125% showed the highest estimated TA (0.29%) for the rate of 25%, and the lowest (0.20%) for the rate of 119%, estimated in with a quadratic fit of the data (Fig. 15F).

Soares et al. (2012) found similar results for tomato crops under different water regimes, finding the highest TA with IWL of 84% and 98% of the crop evapotranspiration in plants at the vegetative and flowering stages. Tomatoes of the salad group present, in general, mean TA between 0.22% to 0.44% (Resende, 1995; Shi et al., 1999; Fernandes, 2000).

The OM source showed the highest estimated TA (0.47%) for the IWL of 50%, and the lowest (0.24%) for the IWL of 76%, estimated with a quadratic fit of the data (Fig. 16A). The IWL with the MAP source showed no significant difference in TA (Fig. 16A). The interaction between the factors was significant for TA with the IWL of 50%, 75%, 100%, and 125%. The TA increased 43.75%, 76.19%, and 36% with the IWL of 50%, 75%, and 125%, respectively, and the OM source resulted in higher TA than the MAP source. Contrastingly, the IWL of 100% showed a higher increase in TA (10.81%) with the MAP source (Fig. 16B).

Lacerda et al. (2016) evaluated physical and physicochemical attributes of tomato fruits and found lower TA in organic plants with no significant differences, but they higher TA in plants of the control treatment. Shirahige et al. (2010) evaluated the yield and quality attributes of tomato fruits and found TA between 0.28% and 0.41%.

Significantly different TA was found between the P sources MAP and OM for the rates of 25%, 50%, and 200%, with

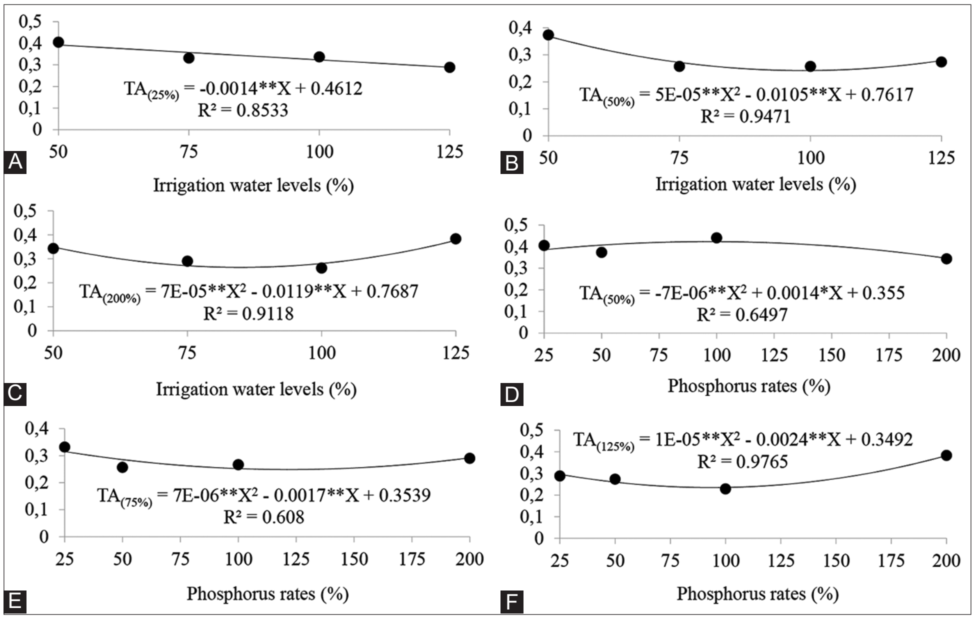

Fig 15. Titratable acidity (TA) of tomato fruits as a function of irrigation water levels (IWL) (A, B and C) and phosphorus rates (D, E, and F).

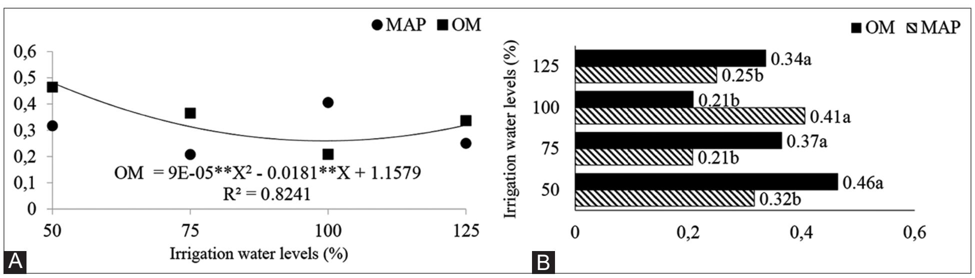

Fig 16. Titratable acidity (TA) of tomato fruits as a function of irrigation water levels (IWL) (A) and phosphorus sources (B).

increases of 12.5%, 23.07%, and 20.68%, respectively; whereas no significant effect was found for the rate of 100% (Fig. 17).

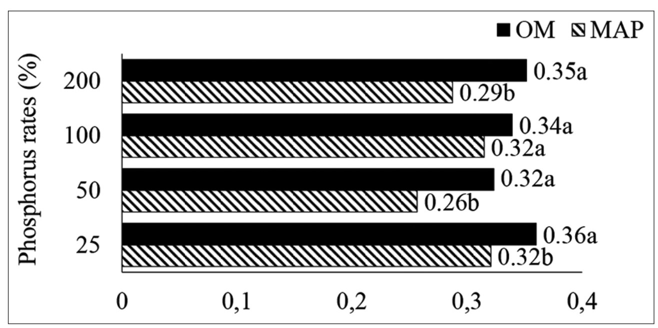

Fig 17. Titratable acidity (TA) of tomato fruits as a function of phosphorus rates and sources.

The results found for TA of tomato fruits were consistent with those of other studies evaluating the quality of organic and conventional tomatoes, which reported TA between 0.38% to 0.41% (Carvalho Tessarioli Neto, 2005), 0.38 and 0.43% (Modolon et al., 2012), and 0.25 and 0.31% (Santos Neto et al., 2016).

The rate of 25% showed the highest estimated TSS/TA (13.57) for the IWL of 90%, and the lowest (10.36) for the IWL of 50%, estimated with a quadratic fit of the data (Fig. 18A). The rate of 50% showed the highest estimated TSS/TA (19.74) for the IWL of 88%, and the lowest (11.77) for the IWL of 50%, estimated with a quadratic fit of the data (Fig. 18B).

The rate of 100% showed the highest TSS/TA for the IWL of 125%, estimated in 21.51 with a linear fit of the data (Fig. 18C). The rate of 200% showed the highest estimated TSS/TA (20.40) for the IWL of 86%, and the lowest (10.59) for the IWL of 125%, estimated with a quadratic fit of the data (Fig. 18D).

The IWL of 50% showed the highest TSS/TA for the rate of 200%, estimated in 13.60 with a linear fit of the data (Fig. 18E). The IWL 100% showed the highest TSS/TA (24.04) for the rate of 200%, estimated with a linear fit of the data (Fig. 18F). The IWL of 125% showed the highest estimated TSS/TA (21.47) for the rate of 113%, and the lowest (10.62) for the rate of 25%, estimated with a quadratic fit of the data (Fig. 18G).

Guimarães et al. (2008) evaluated the production and flavor of tomato fruits and found TSS/TAT higher than 10.

Santos Neto et al. (2016) evaluated the quality of tomato fruits and found higher TSS/TA for organic treatments when compared to the conventional treatments. Schwarz et al. (2013) evaluated the agronomic performance and the physicochemical quality of tomato crops and found mean TSS/TA between 10.6 and 12.6.

The highest TSS/TA was found for the IWL of 97%, estimated in 19.93 with the OM source, which was higher than that found with the MAP source. The lowest TSS/TA (6.91) was found for the IWL of 50%, estimated with a quadratic fit of the data. The IWL with the MAP source showed no significant differences in TSS/TA (Fig. 19A). The interaction between the factors was significant for TSS/TA with the IWL of 50%, 75%, and 125%, and the highest TSS/TA was found with the MAP source, presenting increases of 64.33, 79.93, and 26.26%, respectively. Contrastingly, the OM source showed higher TSS/TA than the MAP source with the IWL of 100%, presenting an increase of 126.41% (Fig. 19B).

The analysis of P rates within each P source showed the highest TSS/TA for the rate of 137%, estimated in 16.50 for the OM source, which was higher than that found for the MAP source. The lowest TSS/TA was found for the rate of 25%, estimated in 11.55 with a quadratic fit of the data. The phosphorus rates with the MAP source showed no significant differences in TSS/TA (Fig. 20A). The interaction between the factors was significant for TSS/TA with the rates of 25% and 50%, and the MAP source showed higher TSS/TA than the OM source, presenting increases of 18.09% and 23.80%, respectively (Fig. 20B).

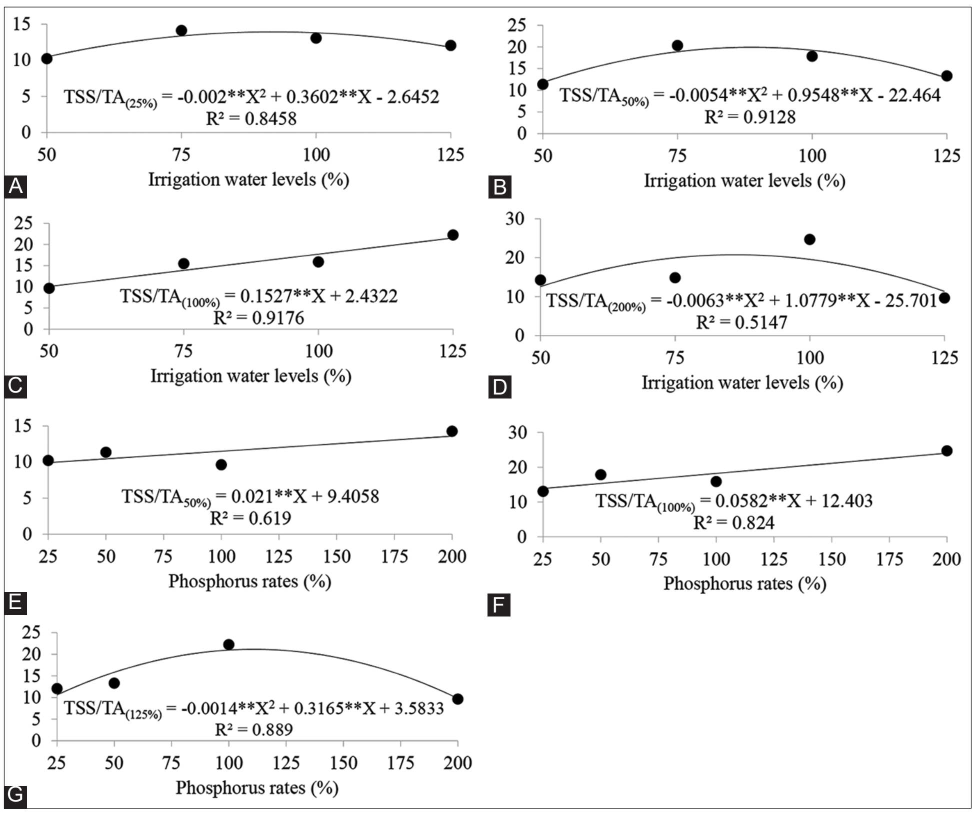

Fig 18. Total soluble solid to titratable acidity ratio (TSS/TA) of tomato fruits as a function of irrigation water levels (IWL) (A, B, C, and D) and phosphorus rates (E, F, and G).

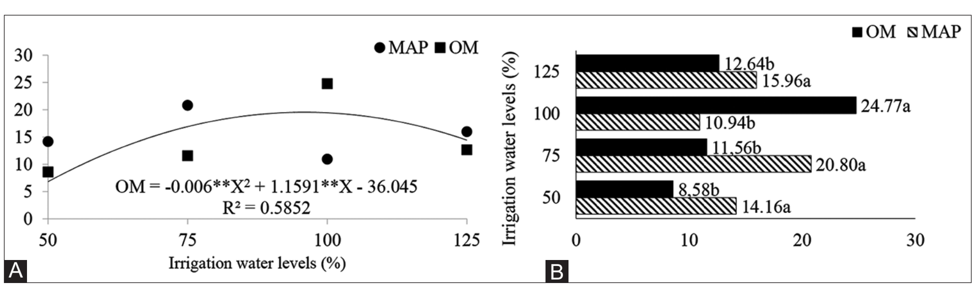

Fig 19. Total soluble solid to titratable acidity ratio (TSS/TA) of tomato fruits as a function of irrigation water levels (IWL) (A) and phosphorus sources (B).

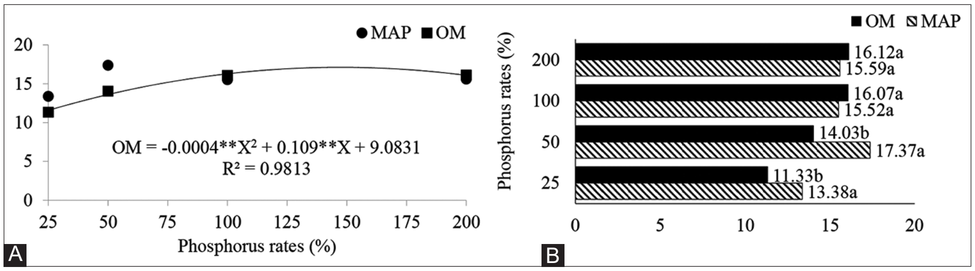

Fig 20. Total soluble solid to titratable acidity ratio (TSS/TA) of tomato fruits as a function of rates (A) and sources (B) of phosphorus.

Barankevicz et al. (2015) evaluated physical and physicochemical characteristics of tomato fruits and found significant difference in TSS/TA, which was estimated in 12.27% with a quadratic fit of the data. Thus, a high TSS/TA is related to combination of sugars and acids, which promotes a mild flavor to tomato fruits and increases the sensorial acceptance of consumers (Ferreira et al., 2004).

CONCLUSIONS

The use of phosphorus (P) rates of 25%, 100%, and 200% of the recommended rate resulted in tomato fruits with longer longitudinal diameters, when these rates were combined with the irrigation water level (IWL) of 125% of the field capacity. The use of P rate of 50% resulted in tomato fruits with larger longitudinal diameters, when these rates were combined with IWL of 50%. The use of P fertilizer from an organo-mineral source resulted in tomato fruits with higher titratable acidity and larger longitudinal diameters, when combined with IWL of 50% or 125%; and in tomato fruits with larger transversal diameters, when combined with IWL of 105%. The use of P fertilizer from an monoammonium phosphate source resulted in tomato fruits with larger longitudinal and transversal diameters, when combining a P rate of 25% and IWL of 125%. The use of P rate of 25% combined with IWL of 77% or 100% resulted in tomato fruits with higher total soluble solid contents and potential hydrogen (pH). The use of the P rate of 137% resulted in tomato fruits with higher total soluble solid to titratable acidity ratio, when using the organo-mineral source.

Contributions of the authors

Oswaldo Palma Lopes Sobrinho: general planning; sample collection; conduction of the experiment; analyses, tabulation, and interpretation of the data; and writing of the manuscript.

Leonardo Nazário Silva dos Santos: planning; monitoring of the experiment; assistance in data interpretation; and review of the manuscript.

Frederico Antonio Loureiro Soares: assistance in the analyses; assistance in data interpretation; and review of the manuscript.

Fernando Nobre Cunha: planning; monitoring of the experiment; assistance in the interpretation of data; and review of the manuscript.

Vitor Marques Vidal: planning; monitoring of the experiment; assistance in data interpretation; and review of the manuscript.

Marconi Batista Teixeira: planning; assistance in the conduction of the experiment; assistance in data interpretation; and review of the manuscript.

Mateus Neri Oliveira Reis: assistance in the data analyses; and review of the manuscript.

Luiz Fernando Gomes: assistance in the monitoring of the experiment; and review of the manuscript.

Jaqueline Aparecida Batista Soares: assistance in the monitoring of the experiment; and review of the manuscript.

All authors read and approved the manuscript.

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