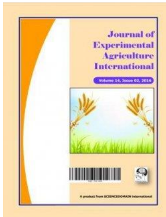

Journal of Experimental Agriculture International

21(2): 1-10, 2018; Article no.JEAI.39849
ISSN: 2457-0591
(Past name: American Journal of Experimental Agriculture, Past ISSN: 2231-0606)

Development and Productivity of Tomato Plants under Water Deficit

Marlla de Oliveira Hott[1*], Edvaldo Fialho dos Reis[1], Victor Luiz Souza Lima[1], Lucas Rosa Pereira[1] and Giovanni de Oliveira Garcia[1]

[1]Centro de Ciências Agrárias e Engenharias, Universidade Federal do Espírito Santo, Alto Universitário s/n, CP 16, CEP 29500-000, Alegre, ES, Brazil.

Authors' contributions

This work was carried out in collaboration with all authors. Author MOH designed and developed the study and wrote the first draft of the manuscript. Author EFR managed the projection and development of the study, and performed the statistical analysis. Author VLSL collaborated in the development of the study, managed the preparation of the manuscript, performed the first corrections, made the charts and tables. Author LRP collaborated in the implementation, development, and evaluation of the data of the experiment and aided in the searches of literature. Author GOG collaborated in the projection and analysis of the study. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JEAI/2018/39849
Editor(s):
(1) Dalong Guo, Professor, College of Forestry, Henan University of Science and Technology, Luoyang, People's Republic of China.
Reviewers:
(1) Alexandra Tomaz, Instituto Politécnico de Beja, Portugal.
(2) Kürşad Demirel, Canakkale Onsekiz Mart University, Turkey.
Complete Peer review History: http://www.sciencedomain.org/review-history/23521

Original Research Article

Received 21st December 2017
Accepted 1st March 2018
Published 8th March 2018

ABSTRACT

Aims: The objective of this study was to evaluate the influence of five soil water tensions on the development of table tomato in the vegetative and productive stages, under greenhouse conditions.
Study Design: The experiment was installed in a completely randomized design, in a 5 x 2 subdivided plot scheme, with five replicates.
Place and Duration of Study: The experiment was conducted between April and July 2014, in a greenhouse of the Universidade Federal do Espírito Santo, in Alegre, ES, Brazil.
Methodology: Tomato seedlings were transplanted to the pots (50 dm^3), which were arranged on the ground with a spacing of 1.0 x 0.5 m, between rows and plants, respectively. Irrigation was performed to maintain the matric potential within the range between the field capacity (10 kPa) and

**Corresponding author: E-mail: marllahott@yahoo.com.br;*

the required tension in each plot (15, 25, 40, 55, and 70 kPa). The plants were evaluated for height, number of flowers, root dry mass, dry mass of the aerial part of the plant, fruit yield, fruit mass, productivity, and fruit diameter.
Results: At 33 days, the plants presented higher height (98.48 cm) at 31.71 kPa (R^2 = 0.99), while at 90 days the plant height decreased linearly as a function of the increase in soil water tension (R^2 = 0.94). Aerial and root biomass were significantly influenced by water tension (P < .01), decreasing linearly as tension increased. The number of flowers produced per plant was inversely proportional to the water tension in the soil (P < .01). The fruit yield, productivity, fresh fruit mass, and longitudinal fruit diameter variables were significantly influenced by soil water tension (P < .01). The largest fruit diameter (62.49 mm) was obtained at 15 kPa (R^2 = 0.99).
Conclusion: The table tomato responded differently to soil water tension at vegetative and productive stages.

Keywords: Vegetative stage; productive stage; water deficit; irrigation management.

1. INTRODUCTION

Water scarcity affects over 40% of the global population due to overconsumption in the agricultural sector, especially in some countries where groundwater use exceeds the natural recharge capacity [1]. Although Brazil has a large water supply compared to other countries, the spatial distribution and the demand are heterogeneous, compromising the use in some regions. In addition, the irregularity in the precipitation regime has intensified in recent years and contributed to the extreme events related to water [2]. In Southeast Brazil, accumulated rainfall remains below the annual historical average since 2013, when the water crisis began. In 2015, the State of Espírito Santo decreed a critical drought event in 38% of the municipalities [3].

In the national territory, the irrigation sector accounts for 55% of the total withdrawals and 75% of the consumption flow [3]. The irrational use of water in irrigated agriculture, combined with the contamination of water bodies, intensified by industrial development and urban growth, contribute to the aggravation of the water crisis [4]. However, it is estimated that by 2050 food production will be increased by 60% to meet the demand of a population of more than nine billion people [1]. Therefore, the proper use of irrigation is essential because water is the most limiting factor to crop yield [5] and its inadequate supply reduces food production [6].

There are several types of irrigation systems, with dripping being one of the most efficient in water application [7]. However, regardless of the type of system implemented, irrigation management is fundamental to increase crop productivity and water-use efficiency [8]. In irrigation management with a tensiometer, water should be provided whenever the tension reaches a critical value so that it does not affect the crop performance. The amount of water supplied is based on the water storage capacity in the soil [9].

The tomato (*Solanum lycopersicum* L.) plays a significant economic role as a vfruit, with the largest cultivated area in the world. However, water is one of the main elements that affect its production [10]. However, throughout the cycle, the crop presents a variation in water demand [11]. In this scenario, it is recommended that irrigation management is carried out based on the phenological stage, both to increase tomato production and to reduce water waste [9]. It is recommended that tensions of 35, 12, and 15 kPa be used for cultivation of tomatoes for processing in the vegetative, fruiting, and maturation stages, respectively [8]. However, for table tomatoes, there are a few stress-related studies that maximize productivity. The objective of this study was to evaluate the influence of five soil water tensions on the development of table tomato in the vegetative and productive stages, under greenhouse conditions.

2. MATERIALS AND METHODS

2.1 Place of Study and Preparation of Soil

The experiment was conducted between April and July 2014, in a greenhouse (30 ± 5 °C temp., 60 ± 10 % RH, 12 h photoperiod) located in the experimental area of the Center of Agrarian Sciences and Engineering of the Universidade Federal do Espírito Santo (CCAE-UFES), in Alegre, ES, Brazil. The climate of the region is of type "Aw" with the dry season in the winter, according to the classification of Köppen [12], presenting a temperature and average annual rainfall of 23ºC and 1200 mm, respectively.

The soil used in the experiment was classified as Red–Yellow Latosol according to the Brazilian Soil Classification System (SiBCS) [13]. Soil collection was carried out in the experimental area of the CCAE-UFES at a depth of 0 to 0.30 m. The soil was unstructured and crossed by a 4 mm sieve and homogenized. The soil was corrected using the base saturation method, according to the chemical analysis (Table 1), applying 1.5 kg of limestone in 2.5 m^3 of soil, at 25 days, before transplantation of the tomato seedlings. After the chemical correction, the soil was fertilized with 30 kg of chicken manure and a sample was taken for physical and water analysis.

The soil was accommodated in pots with a capacity of 50 dm^3, where chemical fertilization was carried out according to the methodology proposed by Novais et al. [14] for controlled environment. The tomato seedlings ('Alambra' cv.) were transplanted to the pots, which were arranged on the ground with a spacing of 1.0 x 0.5 m, between rows and plants, respectively. During the experiment, additional fertilization was performed based on the Manual of Recommendation of Liming and Fertilization for the Espírito Santo State, 5th approach [15].

2.2 Experimental Design

The experiment was installed in a completely randomized design, in a 5 x 2 subdivided plot scheme. The plots consisted of soil water tensions at five levels (15, 25, 40, 55, and 70 kPa) and the subplots constituted stages of development of the tomato at two levels (vegetative and productive). Five replicates were performed. Irrigation was performed to maintain the matric potential within the range between the field capacity (10 kPa) and the required tension in each plot (15, 25, 40, 55, and 70 kPa). The period corresponding to the vegetative stage was between the transplanting of the seedlings and the thirty-third day after transplanting the seedlings (DAT), and the productive stage was from the thirty-fourth DAT to the ninetieth DAT. In the thirty-third DAT, the plants that comprised of the vegetative stage were evaluated and cut. The experimental units corresponding to the productive stage were evaluated at the ninetieth DAT.

2.3 Irrigation Management

The water was applied through a drip irrigation system with a flow rate of 2 L. h^{-1}. Two tensiometers were installed in each treatment, at a depth of 0.2 m, and the irrigation moment was determined by means of the tensiometers. To enable the use of tensiometers, the water retention curve was obtained according to the Brazilian Agricultural Research Corporation [16]. The curve was adjusted to the soil according to the model proposed by Van Genuchten [17]. The volumetric moisture and the water replacement slide for each treatment were determined. The irrigation time for the soil to return to the field capacity was determined by the ratio between the water replacement slide and the dripper flow rate, assuming 90% application efficiency [7]. The physical-water characteristics of the soil are described in Table 2.

2.4 Cultivation

The tomato seedlings were conducted fifteen days after transplanting, in a Mexican system [18], with two stems per plant. Pruning was performed once a week. Pruning of the apical bud was performed 55 days after transplanting of the seedlings, when the plants presented between eight and ten clusters. Control of invasive plants was done manually, when necessary. The phytosanitary control was carried out preventively using the recommended products for the tomato crop according to the Brazilian Ministry of Agriculture, Livestock, and Supply (MAPA).

Table 1. Chemical attributes of the red-yellow latosol used as substrate for planting tomato

pH	P	K	Ca	Mg	Al	H+Al	CEC	T	V
	mg dm^{-3}				cmol$_c$ dm^{-3}				%
5.3	3.0	69.0	1.2	0.8	0.1	4.5	6.7	2.3	32.7

Extraction and determination: pH in water (1:2.5); P, K: Mehlich 1; Ca, Mg, Al: KCl (1M); H=Al: Calcium acetate (0.5M), CEC at pH 7

Table 2. Physical-water characteristics of the soil used as substrate for tomato planting

FC	WP	AW	Ds	Sand	Silt	Clay
	$m^3.m^{-3}$		$g.cm^{-3}$		$g.kg^{-1}$	
0.270	0.176	0.094	1.116	302.56	63.4	634.04

Field Capacity (FC), Wilting point (WP), Available water (AW), Soil density (Ds)

2.5 Characteristics Evaluated

The plants corresponding to the vegetative stages were evaluated for height, number of flowers, root dry mass, and dry mass of the aerial part of the plant. The height of the plant was measured from the cervix to the apex, using a scale graded in centimeters. The number of flowers was obtained by direct counting in each plant. To determine the dry mass of the aerial part of the plant and root, the samples were placed in a drying oven at 65ºC until reaching a constant mass, which was monitored using an analytical balance.

In the productive stage the height of plants, fruit yield, fruit mass, productivity per plant, and fruit diameter was evaluated. The fruit yield was determined by direct counting of the fruits that were on the plant at 90º DAT and added to the number of fruits that had already been harvested from the plant [19]. The fruit mass was obtained by the average weight of the fruits harvested. The productivity, expressed in kilograms per plant, was found by multiplying the average mass of the fruits by the yield of the plant. The diameter of the fruits was measured with a digital pachymeter. The classification of the fruits was carried out according to the system proposed by the Ministry of Agriculture, Livestock, and Supply [20]. This system was proposed for the marketing of tomatoes for consumption in natura, between MERCOSUR member countries and the Brazilian domestic market.

2.6 Statistical Analysis

The effect of the water tensions on the variables was analyzed by regression using the SAEG 9.1 software [21].

3. RESULTS

All characteristics evaluated in tomato plants were influenced by soil water tension, indicating that the vegetative and productive stages of the tomato could be affected by the water availability. The plants completed the development cycle and produced fruits at all soil water tensions evaluated.

At 33 DAT, the data presented a quadratic adjustment for the height variable (R^2 = 0.99), with the highest value (98.48 cm) being estimated for the tension of 31.71 kPa (Fig. 1). A small difference was observed between the maximum plant height, estimated for the tension of 31.71 kPa, and the height of the plants grown at 25 kPa (0.5%) and 40 kPa (0.8%). However, when compared to the tension of 15 kPa, the increase was 3%. It was observed that at 90 DAT the plant height decreased linearly as a function of the increase in soil water tension (R^2 = 0.93), varying from 225 cm in the tension of 15 kPa to 165.2 cm at 70 kPa (Fig. 1). The plants submitted to a tension of 15 kPa presented a height 4.8% and 12% greater than the plants submitted to tensions of 25 kPa and 40 kPa, respectively.

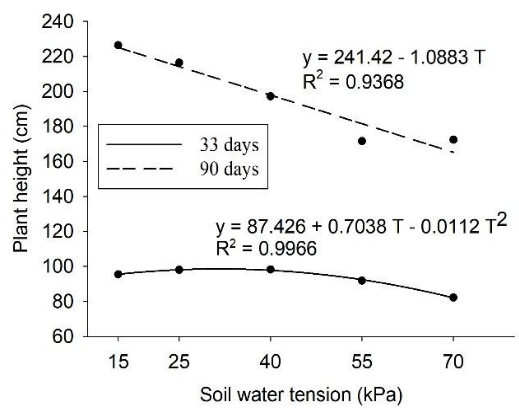

Fig. 1. Height of tomato plants (cm) 33 and 90 days after transplanting of seedlings under different soil water tensions (15, 25, 40, 55, and 70 kPa)

Aerial biomass and root biomass were influenced by soil water tension (R^2 = 0.91; R^2 = 0.95), decreasing linearly as tension increased (Figs. 2 and 3). The higher water availability increased the biomass production in the aerial part by 41% when compared to lower water availability (Fig. 2). In contrast, the root biomass varied between 14.7 g and 11.9 g, which corresponded to the reduction of 19% of the tension from 15 kPa to 70 kPa (Fig. 3).

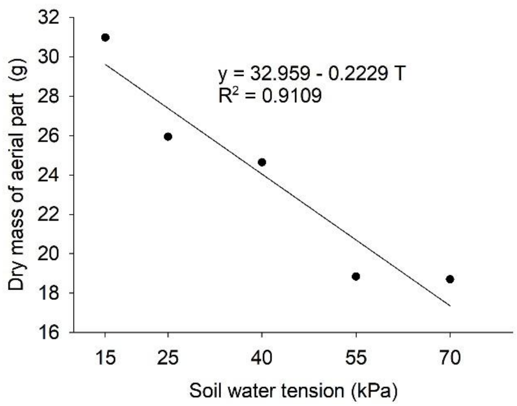

Fig. 2. Dry mass of aerial part of tomato plants 33 days after transplanting of seedlings under different soil water tensions (15, 25, 40, 55 and 70 kPa)

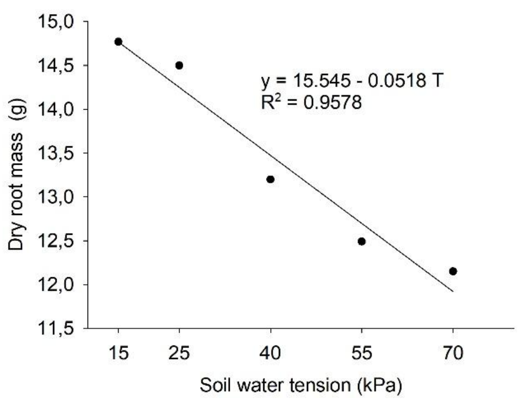

Fig. 3. Dry root mass of tomato plants 33 days after transplanting of seedlings under different soil water tensions (15, 25, 40, 55 and 70 kPa)

The number of flowers produced per plant at 33 DAT was inversely proportional to the water tension in the soil (Fig. 4). It was observed that the emission of flowers in plants submitted to the tension of 15 kPa was 7% higher than 25 kPa and 38.4% higher than 70 kPa (R^2 = 0.82; Fig. 4).

The fruit yield, productivity per plant, fresh fruit mass, and longitudinal fruit diameter variables were influenced by soil water tension (Figs. 5, 6, 7 and 8, respectively). Fruit yield presented quadratic adjustment as a function of soil water tension (R^2 = 0.8155, Fig. 5). It was verified that the maximum production (63.92 fruits.plant^{-1}) estimated for the tension of 20.42 kPa was only 0.5% and 0.3% higher than the production reached with the tensions of 15 kPa and 25 kPa, respectively (Fig. 5). However, the number of fruits produced at 70 kPa presented a reduction of 38% compared to the maximum production (Fig. 5).

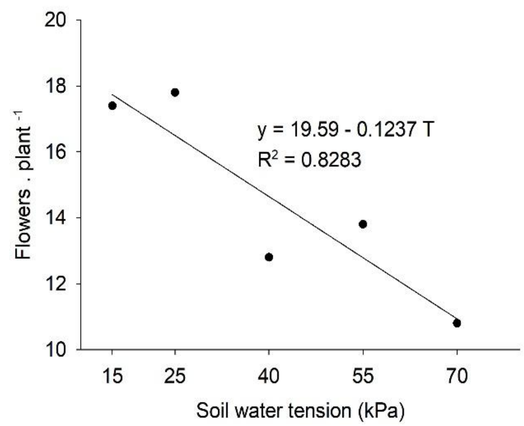

Fig. 4. Number of flowers in tomato plants 33 days after transplanting of seedlings under different soil water tensions (15, 25, 40, 55, and 70 kPa)

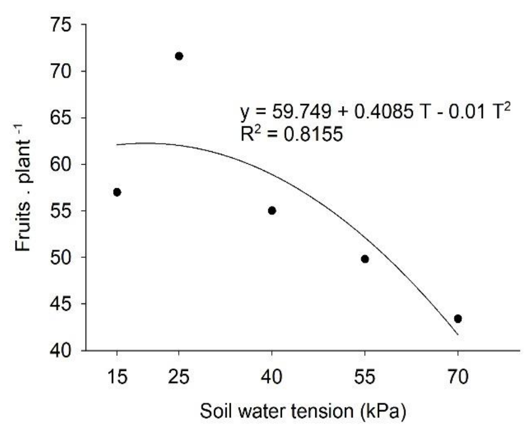

Fig. 5. Number of fruits in tomato plants under different soil water tensions (15, 25, 40, 55, and 70 kPa)

A quadratic fit (R^2 = 0.81) maximized the productivity (6.69 kg.plant^{-1}) at 21.13 kPa (Fig. 6). It was observed that the plants cultivated at 15 kPa and 25 kPa showed reduced productivity by 0.9% and 0.3%, respectively, compared to the maximum productivity (Fig. 6). However, at 70 kPa the reduction in productivity was 53.5% (Fig. 6).

The water tension in the soil showed a linear adjustment for the mass of the tomato fruits (Fig. 7). It was found that the fresh mass ranged from 117.2 g at a tension of 15 kPa to 81.1 g at a tension of 70 kPa (Fig. 7). When compared to 15 kPa, the tension of 25 kPa produced fruits with 5.5% less mass (Fig. 7). There was a high correlation between the water availability and the response to this variable (R^2 = 0.99; Fig. 7).

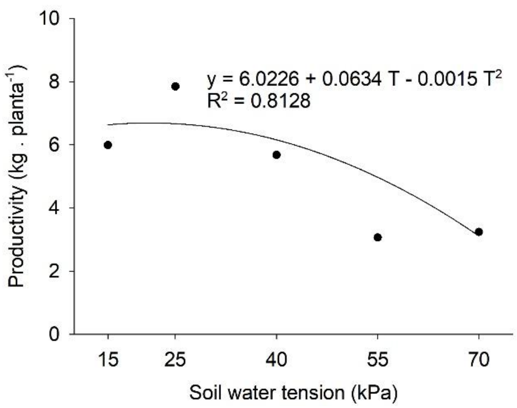

Fig. 6. Productivity (kg.plant^{-1}) of tomato plants under different soil water tensions (15, 25, 40, 55, and 70 kPa).

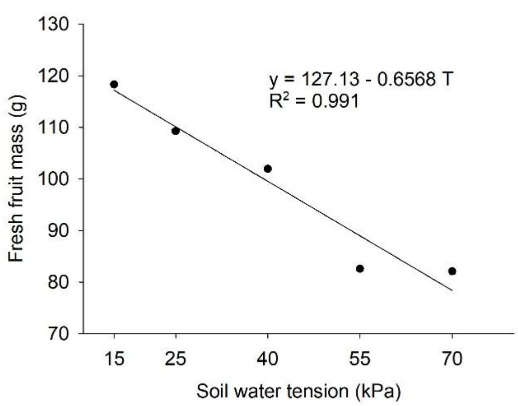

Fig. 7. Fresh mass of tomato fruits under different soil water tensions (15, 25, 40, 55, and 70 kPa)

The largest fruit diameter (62.49 mm) was obtained at the tension of 15 kPa, which was 2.2% higher than the diameter obtained at 25 kPa (R^2 = 0.99; Fig. 8). However, the fruits produced at 70 kPa were 12% lower in diameter than the fruits produced at 15 kPa (Fig. 8). According to the standards for classification of tomato fruits of the Brazilian Ministry of Agriculture, Livestock and Supply [20], all fruits produced were classified as small, having a transverse diameter between 50 mm and 65 mm.

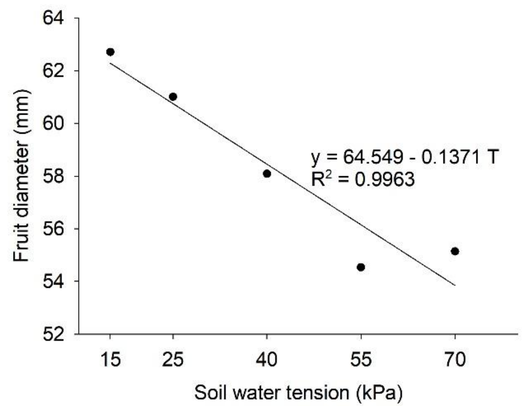

Fig. 8. Fruit diameter of tomato plants under different soil water tensions (15, 25, 40, 55, and 70 kPa)

4. DISCUSSION

The results obtained in this study indicate that the table tomato requires different amounts of water for the vegetative and productive stages. The best vegetative development of the table tomato occurred at a tension of 32 kPa. Although the tension of 15 kPa increased the biomass production and the emission of flowers, the plants subjected to this tension were not the most productive. The productive development of the table tomato was maximized by a tension of 21 kPa, which provided higher fruit yield and productivity. However, the tension of 15 kPa promoted increases in mass and fruit diameter.

During the vegetative stage, the tensions of 25 kPa and 40 kPa stimulated the growth of the plants of similar form, and they reached heights greater than the plants submitted to a tension of 15 kPa. The small variation between the maximum height estimated at 32 kPa and the height obtained with tensions of 25 kPa and 40 kPa (Fig. 1), together with the lower growth of the plants submitted to 15 kPa, indicate that the tomato has a lower water demand in the vegetative stage. The lower water consumption may be associated with the low evapotranspiration surface of the tomato during the vegetative period [22]. However, in the productive stage, the increase in height was favored by the tension of 15 kPa (Fig. 1). In this stage, plants have a higher evapotranspiration surface [22] and need to assimilate more CO_2 to meet the demand of flowers and fruits, in detriment to vegetative growth [23]. Therefore, the increase in the water demand of the plants may have made the vegetative growth more sensitive to the variation of soil moisture in the productive period.

The high biomass production in the greatest water availability (Fig. 2) can be justified by one of the most important processes that occur in plants — Loss of water through transpiration, to assimilate carbon dioxide [24]. Physiologically, the diffusion of CO_2 is made possible by the stomatal opening during transpiration. However, stomatal closure is one of the main vegetation mechanisms to prevent water loss and entails the reduction of photo-assimilates [25], which may have contributed to the lower accumulation of biomass in tomatoes subjected to higher water stress in the soil. Tomatoes submitted to a tension of 70 kPa had the development of the root system reduced by 56.31% compared to 15 kPa [26]. Moreover, Silva et al. [27] found an increase of 43% for root dry mass and 70% for dry mass of the aerial part, when comparing the highest and lowest water blade. Although the values found in this study are lower than those obtained by the cited authors, the results are consistent with them. It is observed that the decrease in the biomass of the aerial part due to the increase in the water tension was higher than the decrease that occurred in the biomass of the root (Fig. 2). This difference was expected because, under water-deficit conditions, there is greater root expansion due to lack of moisture at the soil surface [10,25]. On the other hand, low water availability causes a reduction in the leaf area to avoid transpiration [27, 28], which may have contributed to the occurrence of greater variations in the biomass of the aerial part.

The increase in the number of flowers promoted by higher water availability (Fig. 3) may be related to the production of biomass stimulated by the tension of 15 kPa. The net gain of carbon and energy generated through the assimilation of CO_2 is converted into biomass [24] and used according to the plant demand [25]. However, the plants that possibly assimilated more CO_2 emitted a greater number of flowers, whereas, the plants submitted to the greater tensions of water in the soil produced less biomass and consequently reduced the production of flowers.

Although the lower tension has maximized the production of flowers and this variable evidence the amount of fruits that the plant can produce, the maximum yield and productivity were not obtained at 15 kPa. Surprisingly, plants grown under 25 kPa of tension produced more fruits and exceeded the productivity of plants submitted to 15 kPa. Maintaining the same tension throughout the tomato cycle, Moreira et al. [29] verified that the productivity obtained with the tension of 28.5 kPa was higher than the tension of 15 kPa. However, the use of controlled water deficit during the vegetative stage benefited the production of tomatoes [10], while the use of tensions below 35 kPa during this period could affect plant productivity [8]. Therefore, it can be inferred that the production of tomatoes submitted to 15 kPa was influenced by the use of this tension during the vegetative stage.

The physiological processes that contributed to the production of tomato fruit were not evaluated in this study. However, there is evidence that the biomass production potentiated at 15 kPa, promoted the production of flowers, but did not maximize fruit yield. However, loss of yield is caused by problems related to flowering and not to fruit formation [30]. Perhaps, the low tensions during the vegetative stage are detrimental to yield by stimulating biomass production and inducing floral production above the plant's capacity, to meet its demand for photoassimilates [31], intensifying abortion, and falling flowers [32]. It is worth mentioning that in order to understand the influence of the use of tension 15 kPa at the vegetative stage on the number of fruits produced, new experiments are needed to monitor the production and destination of photoassimilates in each studied tension.

The fresh mass and the diameter of the fruits were potentialized by the tension of 15 kPa, with their values reduced as the soil water tension increased (Fig. 5). The fresh mass obtained with the highest water availability was 30.8% higher than the tension of 70 kPa. This result was lower, however, consistent with that of Silva et al. [32], who observed a 143% amplitude for fruit mass. Increased fruit mass was also observed by Marouelli and Silva [8,33], by using tensions lower than 15 kPa during the productive stage of the tomato. Ismail et al. [34] concluded that the water content in the soil was the main factor that determined the average weight of the fruit. The fruit growth was mainly related to the photosynthetic capacity and the distribution of photoassimilates between the different plant tissues [35]. However, low CO_2 assimilation limited by water deficit [36] reduced the carbohydrate supply to fruits, reducing their fresh weight, and consequently, the productivity of tradable tomatoes [23].

About the diameter of the fruits, the difference between the values obtained with the highest and lowest tension evaluated was 12%. Corroborating with these results, Silva et al. [32] and Koetz et al. [37] verified a reduction of 35% and 5%, respectively, in the diameter of fruits, as a function of the increase in the water deficit. According to Koetz et al. [37], the diameter of the fruit can be increased or reduced through the applied water blade. As ripe tomatoes are composed of 95% water [11], higher water availability provides higher fruit diameters. It is worth noting that the phloem sap is the main source of water for fruit, contributing to most of its volume [38,39,40,41]. However, the transport of the elaborated sap, among other physiological processes such as turgidity, stretching, division, and cellular expansion is limited by the water deficit [25], hindering fruit growth.

The use of the tension 21 kPa throughout the crop cycle has demonstrated a potential to increase fruit yield and productivity per plant. However, the water demand of the tomato varies according to its phenological stage [10]. Therefore, to improve the water-use efficiency, it is suggested to perform irrigation management according to the developing phases of the tomato. The results obtained in this study indicate that the plants develop better with a tension of 32 kPa during the vegetative stage. However, the data evaluated in this experiment are insufficient to propose an irrigation management based on the phenological phases of the tomato, as the tension used during the productive stage has been also used in the vegetative stage. Thus, it is suggested to carry out new studies that use the tension of 32 kPa during the vegetative stage and lower tensions during the productive stage.

5. CONCLUSION

The table tomato responded differently to soil water tension at vegetative and productive stages. During the vegetative stage, the tomato showed higher production of dry biomass and production of flowers at 15 kPa and higher plant height at 32 kPa. At the productive stage, plant height, fresh mass, and fruit diameter were higher at 15 kPa, while fruit yield and productivity were maximized by the tension of 21 kPa.

ACKNOWLEDGEMENTS

The authors would like to thank the Coordenação de Aperfeiçoamento Pessoal de Nível Superior (CAPES) for granting a scholarship to the first author and the Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (FAPES) for their financial support. They would also like to thank the Universidade Federal do Espírito Santo (UFES/CCAE) for the cost aid to implement the experiment and Joabe Martins Silva, Bruno Cesconetto, Pedro Esberard, João Paulo, and field assistants of CCAE, for their support in the installation and conduction of the experiment.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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