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Assessing the Effects of Deficit Irrigation Techniques on Yield and Water Productivity of Processing Tomato

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Given the current water scarcity and aiming at sustainable agricultural development, it is necessary to identify and apply the most appropriate practices for water saving, also considering yield and water productivity improvement. Tomato is a high-water-demand vegetable crop, and excessive use of irrigation water generally leads to overexploitation of groundwater resources and deterioration of the environment. In addition, excess irrigation water leads to low water productivity (yield/water use ratio). Thus, there is an urgent need to increase crop yield with concomitant conservation of water resources. This study aimed to identify the effect of regulated deficit irrigation on the yield and water productivity of tomato cultivar N-901 for industrialization purposes. Deficit irrigation was carried out during the vegetative growth stage, considering different seedling transplanting periods. The experiment was conducted in a greenhouse at the School of Agronomy of the Federal University of Goiás (UFG). The experimental design was a randomized complete block with five replicates, in a 2 x 4 factorial arrangement. The plots were made by combining two periods of irrigation deficit (10 and 20 days after transplanting - DAT) and four soil water tension thresholds (30; 40; 60; and 70 kPa). The results showed that the studied cultivar responded significantly to the water deficit, providing different agronomic development profiles. The tensions of 30 and 60 kPa applied at 10 DAT were the ones that most intensified yield and water productivity without significantly affecting the agronomic development of the crop. Deficit irrigation at 60 kPa was shown to reduce the total volume of water applied during the cycle without significantly reducing crop production compared to the tension of 30 kPa.
Keywords: irrigation strategy, limited irrigation, water saving, morphology and physiology.

1. Introduction

In 2017, the world production of industrial tomato was estimated at 37.5 million tons, Brazil is the eighth largest producer worldwide, with a production of 1.4 million tons (WTPC, 2017). Highlighting the importance of the tomato crop in the Brazilian and worldwide agribusiness, the state of Goias stands out with a production of approximately 1 million tons in 13 thousand hectares of cultivation (IBGE, 2017). Irrigation has contributed to the increased agricultural yield of tomato in Brazil, being used in the agricultural areas with these commodities (Soares, 2012). However, the challenge of irrigated agriculture is to maximize food production with water use efficiency, that is, to increase the production per unit of water through rational and sustainable management of irrigation (Du et al., 2015). Rational management of water presupposes the use of available water resources to maximize production efficiency. Conventional practices are based on 100% crop evapotranspiration replacement and can also be managed by monitoring soil and plant characteristics and conditions. Total water replacement can be performed where the irrigation water is applied to supply the whole demand of the plant, or to manage deficit irrigation (Frizzone, 2007). Controlled water deficit is a management strategy that reduces water use without impairing productivity (Gava et al., 2015). This practice, when applied during plant growth and development, affects physiological and biochemical processes that sustain the production (Du et al., 2015; Vursavus, et al., 2017). Among the responses of plants under water deficit, we can highlight the

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stomatal behavior and interaction with the photosynthetic activity, determining carbon gain and affecting the vegetative and reproductive growth of the plants (Du et al., 2010; Grisafi et al., 2017).

When the soil is less humid, plants respond by reducing transpiration through the regulation of stomatal conductance (Dodd et al., 2015). As a response to the deficit, the root system deepens, so one of the effects of the deficit is increased root volume and weight (Torrecillas, 1996). Water deficit can provide increased crop yield and quality and may lead to additional gains if accurate and real-time assessments of water availability for plant roots are performed (Du et al., 2015).

In this study, deficit irrigation was carried out during the vegetative growth stage, considering different seedling transplanting periods. This study aimed to identify the effect of regulated deficit irrigation on the yield and water productivity of tomato cultivar N-901 for industrialization purposes.

2. Materials and methods

The experiment was carried out in a greenhouse at the School of Agronomy of the Federal University of Goiás (UFG), (coordinates are: 16°32' S latitude, 49° 21' W longitude, and altitude of 730 m). Indoor climatic conditions were controlled at a temperature of 25 °C and relative air humidity of 48% (Alvarenga, 2013). The cultivar used was N-901. Seedlings were transplanted to pots with 0.50 x 0.30 m (depth x diameter), with 0.028 m^3 soil. Initially, tomato seeds were germinated in organically enriched peat, in open plastic trays with a vermiculite cover to facilitate aeration. Table 1 presents information on the physical and chemical properties of the soil.

Table 1: Physical and chemical characteristics of the soil

Texture			Organic matter (%)	pH	P (mg dm^{-3})	K (cmol dm^{-3})	Ca (cmol dm^{-3})
Sand (%)	Silt (%)	Clay (%)					
46.0	20.0	34.0	2.2	6.8	37.9	4.6	2.9

Standard cultural practices were adopted during the crop-growing season. A total of 50 kg N ha^{-1}, 300 kg P_2O_5 ha^{-1}, and 50 kg K_2O ha^{-1} fertilizer were applied according to the recommendations based on soil analyses. During the growing season, weeding was performed manually and neonicotinoid insecticide (Evidence 700 WG®) was applied according to commercial recommendations every seven days from 10 to 50 DAT.

The experimental design was a randomized complete block with three replicates, in a 2 x 4 factorial arrangement. The plots were made by combining two periods of irrigation deficit (10 and 20 days after transplanting - DAT) and four soil water tension thresholds (30; 40; 60; and 70 kPa).

Drip irrigation was performed through self-compensating online dripper (4 L h^{-1}), Click Tif - HD PC, brand NaanDanJain. Lateral lines were composed of 16-mm polyethylene tube, PN 30, and each treatment had an independent control valve at the beginning of each lateral line. Soil moisture monitoring was based on the soil dielectric constant, using a Time Domain Reflectometer (TDR, model EC-5), installed at 0.2 m depth. Data were recorded by an Em50 datalogger. Volumetric moisture content at field capacity (FC) and permanent wilting point (PWP) was determined using a pressure plate apparatus (Richards, 1965). The measured FC (-11.6 kPa) and PWP (-1505.7 kPa) averaged 36 and 21 %, respectively (Walker, 1989).

To evaluate the effect of the different soil water tension levels on the agronomic and productive characteristics of N-901 tomato, root dry matter and whole plant dry matter (stem, leaf, and flower) were measured using a balance with a resolution of 0.01 g. Drying was performed at 80 °C in a forced-circulation oven until constant weight, at 20 and 35 DAT and at harvest, with the manual and definitive removal of the plant. Regarding the root system, the analyzed characteristics were root dry weight and root length. To collect the roots, the soil containing roots was removed, being subsequently washed in running water, and measured with a millimeter ruler at the intersection from the stem to the root apex (Medeiros et al., 2011). After length measurement, the roots were dried until constant weight in a forced-circulation oven at 105 °C (Silva et al., 2017). Growth was monitored by measuring plant height (distance between the ground level and the apical bud) and stem diameter (in the plant neck) in 3 plants per plot at 15, 20, 25, 30, and 35 DAT, when growth stabilized. Each treatment was harvested when ripe fruit rate reached about 85%. Ripe tomato fruits were manually harvested. Fruit yield (g $plant^{-1}$), marketable fruit yield (g $plant^{-1}$), green fruit yield (g $plant^{-1}$), and diseased and deformed fruit yield (g $plant^{-1}$) were observed at each harvest. Water use efficiency (WUE) was determined by the ratio between marketable fruit yield (Kg ha^{-1}) and irrigation water use (mm). Analysis of variance was performed using SISVAR software, and the Tukey test was applied at 5% probability to compare the parameters measured from plants subjected to different deficit irrigation treatments.

3. Results and discussion

Tables 2 and 3 show the effect of deficit irrigation on root characteristics of tomato plants (root dry weight and root length) at 20 DAT, 35 DAT, and at harvest.

Table 2: Effect of soil water tension on root dry weight.

DAT	Soil water tension (kPa)			
	30	40	60	70
	Weight at 20 DAT (g)			
10	10.44^{Ba}	10.02^{Ba}	8.11^{Cb}	11.35^{Aa}
20	10.44^{Aa}	10.44^{Aa}	10.44^{Aa}	10.44^{Ab}
	Weight at 35 DAT (g)			
10	28.46^{Ca}	29.27^{BCa}	33.11^{Aa}	32.35^{ABa}
20	28.46^{Aa}	31.48^{Aa}	28.30^{Ab}	21.50^{Bb}
	Weight at harvest (g)			
10	34.78^{Aa}	37.44^{Aa}	35.58^{Aa}	32.79^{Aa}
20	34.78^{Aa}	32.05^{Ab}	31.61^{Aa}	32.74^{Aa}

Table 3: Effect of soil water tension on root length.

DAT	Soil water tension (kPa)			
	30	40	60	70
	Depth at 20 DAT (cm)			
10	82.47^{Aa}	74.23^{Bb}	73.08^{Bb}	84.26^{Aa}
20	82.47^{Aa}	82.47^{Aa}	82.47^{Aa}	82.47^{Aa}
	Depth at 35 DAT (cm)			
10	96.87^{ABa}	91.39^{BCa}	89.61^{Cb}	100.72^{Aa}
20	96.87^{ABa}	93.94^{Ca}	105.39^{Aa}	99.63^{Ba}
	Depth at harvest (cm)			
10	103.90^{ABa}	100.18^{Bb}	99.30^{Bb}	111.07^{Aa}
20	103.90^{Aa}	107.46^{Aa}	108.94^{Aa}	107.28^{Aa}

Values followed by different uppercase letters in the same line and by different lowercase letters in the same column differ significantly at the 0.05 probability level.

Analyzing root dry weight, there was a significant interaction between the onset of water deficit and the soil water tension for treatments at 60 and 70 kPa, at 20 and 35 DAT. At harvest, only the treatments subjected to 40 kPa showed a significant difference regarding the onset of water deficit. The treatment with earlier onset of water restriction showed a higher root dry weight, having this effect matched after the period of water restriction.

At harvest, treatments subjected to 40 and 60 kPa presented significant differences regarding root length with the application of water deficit, resulting in higher root length when the deficit was started at 20 DAT, except for 70 kPa started at 10 DAT (Table 3).

Similar to Torrecillas (1996), it was observed that the water deficit stimulated root development, both in length and in weight. Brito et al., (2015), analyzing different evapotranspiration replacement rates (60%, 80%, 100%, and 120%) during the vegetative stage in tomato cultivation, verified that the highest root weight represented the highest evapotranspiration replacement rate, with a linear behavior, and the lowest replacement rate accounted for the lowest root dry weight. However, Morales et al. (2015) observed that the closer to the field capacity, the greater the root dry weight. Marouelli and Silva (2007), applying different soil water tensions (6, 10, 15, 30, 60, and 120 kPa), observed an inverse linear behavior of root biomass with increased tension.

Tables 4 and 5 show the effect of deficit irrigation (soil water tension) on the growth parameters plant height and stem diameter, at 15, 20, 25, 30, and 35 DAT.

Table 4: Effect of soil water tension on plant height.

DAT	Soil water tension (kPa)			
	30	40	60	70
	Plant height at 15 DAT (cm)			
10	28.27^{Ba}	31.22^{Aa}	28.27^{Ba}	28.68^{Ba}
20	28.27^{Aa}	28.27^{Ab}	28.27^{Aa}	28.27^{Aa}
	Plant height at 20 DAT (cm)			
10	41.24^{Ba}	42.28^{Ba}	40.05^{Ba}	45.80^{Aa}
20	41.24^{Aa}	41.24^{Aa}	41.24^{Aa}	41.24^{Ab}
	Plant height at 25 DAT (cm)			
10	61.98^{Aa}	60.10^{Aa}	56.22^{Bb}	59.10^{Aa}
20	61.98^{Aa}	61.37^{Aa}	59.37^{Aa}	60.26^{Aa}
	Plant height at 30 DAT (cm)			
10	69.73^{Ba}	72.63^{Ab}	69.08^{Ba}	74.13^{Aa}
20	69.73^{Aa}	71.45^{Aa}	70.86^{Aa}	73.62^{Aa}
	Plant height at 35 DAT (cm)			
10	59.07^{Ba}	62.49^{Ba}	67.42^{Aa}	69.31^{Aa}
20	59.07^{Ca}	64.25^{Ba}	70.10^{Aa}	64.66^{Bb}

Table 5: Effect of soil water tension on stem diameter

DAT	Soil water tension (kPa)			
	30	40	60	70
	Stem diameter at 15 DAT (cm)			
10	0.68^{ABa}	0.65^{ABa}	0.60^{Ba}	0.74^{Aa}
20	0.68^{Aa}	0.68^{Aa}	0.68^{Aa}	0.68^{Aa}
	Stem diameter at 20 DAT (cm)			
10	0.70^{Ba}	0.75^{Aa}	$0.71A^{Ba}$	0.75^{Aa}
20	0.70^{Ba}	0.70^{Ab}	0.70^{Aa}	0.70^{Ab}
	Stem diameter at 25 DAT (cm)			
10	0.92^{Aa}	0.93^{Aa}	0.78^{Ba}	0.87^{Aa}
20	0.92^{Aa}	0.72^{Bb}	0.78^{Ba}	0.73^{Bb}
	Stem diameter at 30 DAT (cm)			
10	1.02^{Aa}	1.03^{Aa}	1.01^{Aa}	1.02^{Aa}
20	1.02^{ABa}	1.07^{Aa}	1.00^{Ba}	0.98^{Ba}
	Stem diameter at 35 DAT (cm)			
10	1.13^{ABa}	1.10^{Ba}	1.16^{Aa}	1.04^{Ca}
20	1.13^{ABa}	1.10^{Aa}	1.04^{Bb}	1.00^{Ba}

Values followed by different uppercase letters in the same line and by different lowercase letters in the same column differ significantly at the 0.05 probability level.

With 35 DAT, the treatments showed a linear behavior with increased height as a function of increasing tension, except for 70 kPa starting at 20 DAT. The largest significant plant growth was observed at 60 kPa, started at 20 DAT. The same effect was not observed for stem diameter. That is, the greater the tension, the lower the stem diameter, except for the treatment at 60 kPa started at 10 DAT.

Silva (2017) observed that the water deficit provides smaller diameters and heights of the tomato plant, which diverges from the plant height observed in this study. Soares et al. (2012), studying different evapotranspiration replacement rates in protected environment, observed a linear decrease in the height of tomato plants and an increase in stem diameter with an increased replacement rate, a pattern similar to that observed in the analyses (Tables 4 and 5), in which height was increased with increasing water restriction.

Tables 6, 7, and 8 show the effect of deficit irrigation (soil water tension) on the parameters dry weight of stems, leaves, and flowers, at 20 DAT, 35 DAT, and at harvest.

Table 6: Effect of soil water tension on stem dry weight.

DAT	Soil water tension (kPa)			
	30	40	60	70
	Stem dry weight at 20 DAT (g)			
10	15.02^{Ba}	15.15^{Ba}	15.92^{Aa}	16.69^{Aa}
20	15.02^{Aa}	15.02^{Aa}	15.02^{Aa}	15.02^{Ab}
	Stem dry weight at 35 DAT (g)			
10	58.72^{Aa}	53.55^{Aa}	45.05^{Bb}	59.84^{Ab}
20	58.72^{Ba}	57.92^{Ba}	58.26^{Ba}	71.45^{Aa}
	Stem dry weight at harvest (g)			
10	96.98^{ABa}	100.95^{Aa}	92.33^{Ba}	93.97^{Ba}
20	96.98^{Aa}	102.90^{Aa}	89.74^{Ba}	80.41^{Cb}

Table 7: Effect of soil water tension on leaf dry weight.

DAT	Soil water tension (kPa)			
	30	40	60	70
	Leaf dry weight at 20 DAT (g)			
10	48.91^{Aa}	53.71^{Aa}	42.51^{Bb}	50.83^{Aa}
20	48.91^{Aa}	48.91^{Ab}	48.91^{Aa}	48.91^{Aa}
	Leaf dry weight at 35 DAT (g)			
10	57.98^{Aa}	59.04^{Aa}	66.44^{Aa}	66.78^{Aa}
20	57.98^{ABa}	61.73^{ABa}	51.91^{Bb}	65.53^{Aa}
	Leaf dry weight at harvest (g)			
10	97.17^{ABa}	107.47^{Aa}	97.90^{Aa}	93.58^{Ba}
20	97.17^{Aa}	93.26^{Ab}	93.32^{Aa}	80.66^{Bb}

Values followed by different uppercase letters in the same line and by different lowercase letters in the same column differ significantly at the 0.05 probability level.

Table 8: Effect of soil water tension on flower dry weight.

DAT	Soil water tension (kPa)			
	30	40	60	70
	Flower dry weight at 20 DAT (g)			
10	3.22^{Ba}	3.78^{Aa}	3.71^{Aa}	3.83^{Aa}
20	3.22^{Aa}	3.22^{Ab}	3.22^{Ab}	3.22^{Ab}
	Flower dry weight at 35 DAT (g)			
10	4.25^{Aa}	3.28^{Ba}	3.40^{Ba}	3.27^{Ba}
20	4.25^{Aa}	3.65^{Ba}	3.35^{BCa}	3.07^{Ca}
	Flower dry weight at harvest (g)			
10	39.50^{Aa}	40.47^{Aa}	34.25^{Aa}	37.43^{Aa}
20	39.50^{Aa}	42.60^{Aa}	36.85^{ABa}	32.61^{Ba}

Values followed by different uppercase letters in the same line and by different lowercase letters in the same column differ significantly at the 0.05 probability level.

The analysis done at 20 DAT (Tables 6 and 7) shows a linear increasing behavior of stem dry weight with increasing tension. The treatments 30 and 40 kPa started at 10 and 20 DAT at harvest, presented significant differences regarding the stem dry weight in relation to the others tension. In this same period of analysis, there is a decreases of leaf dry weigh with increasing tension and water restriction, except for the treatment at 40 and 60 kPa started at 10 DAT.

At the end of the irrigation deficit, at 35 DAT, the results showed a trend of increased stem weight as a function of the onset of water restriction. The treatment at 70 kPa led to the highest mass accumulation. However, this effect was not observed in the analyses performed at harvest, for both stem dry weight and leaf dry weight, showing randomness.

Table 8 shows that flower dry weight, at harvest, decreases with increasing tension and water restriction, except for the treatment at 40 kPa.

Thus, water deficit influences plant growth and carbohydrate accumulation, consequently, lower leaf and stem dry weight. At harvest, the increase in tension represented a lower dry weight of stems, leaves, and flowers, mainly for the treatments with the deficit initiated at 20 DAT. This agrees with Brito et al. (2015), Silva (2017), and Marouelli and Silva (2007), who observed a linear increase in the dry weight of stems, leaves, and flowers with decreasing soil water tension.

Table 9: Effect of soil water tension on fruit yield, marketable fruit yield, green fruit yield, and diseased and deformed fruit yield.

DAT	Soil water tension (kPa)			
	30	40	60	70
		Fruit yield (g plant^{-1})		
10	807.00^{Aba}	623.40^{Ba}	763.66^{Aac}	664.93^{Ba}
20	807.00^{Aa}	663.73^{Ba}	654.73^{Bb}	614.07^{Ba}
		Marketable fruit yield (g plant^{-1})		
10	661.47^{Aa}	426.86^{Ba}	615.73^{Aa}	462.66^{Ba}
20	661.47^{Aa}	506.53^{Ba}	492.60^{Bb}	482.13^{Ba}
		Green fruit yield (g plant^{-1})		
10	118.60^{Ba}	167.66^{Aa}	114.53^{Ba}	173.53^{Aa}
20	118.60^{ABa}	134.46^{ABb}	139.06^{Aa}	102.26^{Bb}
		Diseased and deformed fruit yield (g plant^{-1})		
10	26.93^{Aa}	28.86^{Aa}	33.40^{Aa}	28.73^{Aa}
20	26.93^{Aa}	22.73^{Aa}	23.06^{Ab}	29.66^{Aa}

Values followed by different uppercase letters in the same line and by different lowercase letters in the same column differ significantly at the 0.05 probability level.

The production of diseased and deformed fruit did not differ between the tensions in treatments with deficit starting at 10 and 20 DAT. Only at 60 kPa, there is a difference between the onset of the deficit, in which the deficit started at 10 DAT led to a higher production of diseased and deformed fruit, possibly due to the higher total production.

Among the treatments initiated at 10 DAT, green fruit yield was lower statistically in the treatment maintained at 30 and 60 kPa tension; for the treatments initiated at 20 DAT, in turn, the tensions do not differ from each other, except for 60 kPa, which was shown to be superior to 70 kPa.

Table 9 shows that the plants subjected to 30 kPa obtained higher marketable fruit yield in relation to those subjected to other tensions, except for 60 kPa, corroborating with Zhang et al. (2017). Marouelli and Silva (2007) did not obtain a difference in the production per plant, in which the soil water tension during the development stage was reflected in the production.

Studying different water replacement rates, Campagnol et al. (2014) observed a decrease in production and apical rot with water replacement up to 100% evapotranspiration. In contrast, Silva (2017) and Zhang et al. (2017), also evaluating the water replacement rate, found an increase in production up to 100% return of evapotranspiration losses.

Table 10 presents the results regarding the efficient use of water in industrial tomato production. It is observed that the treatments that maintained soil water tension at 30 kPa and 60 kPa starting at 10 DAT were the ones that used water more efficiently (respectively, 106.74 and 116.34 kg ha^{-1} mm^{-1}).

Silva (2017), studying the cultivar Caline IPA 6, verified higher productive efficiency with water replacement close to 100% crop evapotranspiration, a result similar to that found by Soares et al. (2012) with the cultivar Super Marmade. However, Campagnol et al. (2014) concluded that water deficit led to a higher water use efficiency for the cultivar San Vito, and that increased soil water tension increased the productive efficiency.

Table 10: Effect of soil water tension on efficient use of water in industrial tomato production.

Soil water tension (kPa)	Marketable fruit yield (kg ha^{-1})		Irrigation water use (mm)		Water use efficiency (kg ha^{-1} mm^{-1})	
	10 DAT	20 DAT	10 DAT	20 DAT	10 DAT	20 DAT
30	73,500.00		688.57		106.74	
40	47,430.00	56,280.00	593.89	632.85	79.86	88.93
60	68,410.00	54,730.00	588.00	628.93	116.34	87.02
70	51,410.00	53,570.00	585.78	622.46	87.76	86.06

4. Conclusions

Deficit irrigation provided different agronomic development profiles. The tensions of 30 and 60 kPa applied at 10 DAT were the ones that most intensified yield and water productivity without significantly affecting the agronomic development of the crop.

Deficit irrigation at 60 kPa was shown to reduce the total volume of water applied during the cycle without significantly reducing crop production when compared to the tension of 30 kPa.

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