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PRODUTIVIDADE E QUALIDADE DE FRUTOS DE TOMATE EM CONDIÇÕES SEMIÁRIDAS EM RESPOSTA À IRRIGAÇÃO E COBERTURA PLÁSTICA

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1 RESUMO

As alterações climáticas representam uma séria ameaça aos recursos hídricos e à agricultura, necessitando de soluções inovadoras para manter a segurança alimentar. Este estudo investiga os efeitos combinados de diferentes lâminas de irrigação (LI) e da cobertura plástica nas culturas de tomate em regiões áridas, onde a otimização da água é crucial. Foram aplicadas cinco lâminas de irrigação, variando de 65% a 155% da evapotranspiração da cultura (ETc). Os resultados indicaram que o rendimento total, o peso médio dos frutos e o diâmetro (RT, PMF e DF) aumentaram com o incremento da LI, atingindo uma faixa ideal. A maior produtividade da água de irrigação (PA) foi alcançada com uma lâmina de irrigação de 305 mm ciclo^{-1}. A qualidade dos frutos melhorou sob LIs mais baixas, sugerindo potencial relação entre rendimento e qualidade sob estresse hídrico. A lâmina de 577 mm (~124% da ETc) maximizou a produtividade; para PA, 305 mm (65% da ETc). Considerando os resultados, a cobertura plástica não afetou significativamente a produtividade/qualidade ($p>0,05$), provavelmente devido à precipitação de 246 mm. Recomenda-se uma lâmina de 577 mm (~124% da ETc) para obter o máximo rendimento em condições semiáridas na Bahia; estudos futuros devem testar a cobertura em ciclos secos.

Palavras-chave: manejo da água, produtividade da água, estresse hídrico, irrigação por gotejamento, *Solanum lycopersicum* L.

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PRODUCTIVITY AND QUALITY OF TOMATO FRUITS UNDER SEMIARID CONDITIONS IN RESPONSE TO IRRIGATION AND PLASTIC MULCH

2 ABSTRACT

Climate change poses a serious threat to water resources and agriculture, requiring innovative solutions to maintain food security. This study investigates the combined effects of different irrigation depths (ID) and plastic mulch on tomato crops in arid regions, where water optimization is crucial. Five irrigation depths were applied, ranging from 65% to 155% of crop evapotranspiration (ETc). The results indicated that total yield, average fruit weight, and diameter (TY, FW, and FD) increased with increasing ID, reaching an ideal range. The highest irrigation water productivity (IWD) was achieved with an irrigation depth of 305 mm cycle-1. Fruit quality improved under lower IDs, suggesting a potential relationship between yield and quality under water stress. The 577 mm depth (~124% of ETc) maximized productivity; for IWD, 305 mm (65% of ETc) maximized productivity. Considering the results, the plastic mulch did not significantly affect productivity/quality ($p>0.05$), probably due to the rainfall of 246 mm. A cycle of 577 mm (~124% of ETc) is recommended to obtain maximum yield under semi-arid conditions in Bahia; future studies should test the cover in dry cycles.

Keywords: water management, water productivity, water stress, drip irrigation, *Solanum lycopersicum* L.

3 INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is widely cultivated worldwide for processing and fresh consumption (Li *et al.*, 2016). Higher tomato consumption is associated with a lower risk of developing cancer and cardiovascular diseases (Thies *et al.*, 2012, Cheng *et al.*, 2019) especially prostate cancer (Wu *et al.*, 2004; Hori *et al.*, 2011). Brazil is the 9th largest tomato producer (FAO, 2025). In 2023, the total area was ~62,000 ha, production 4.5 Mt (~72 t/ha), with the Northeast representing 18% of the area and 12% of the production (IBGE, 2024). The water deficit is the main restriction on tomato production in Northeast Brazil, where the total annual rainfall varies from 300 to 800 mm and is concentrated in a few months of the year (Crispim *et al.*, 2016).

Water plays an important role in tomato growth (Hou *et al.*, 2016; Agbna *et al.*, 2017), yield (Lovelli *et al.*, 2017), and flower number (Silva *et al.*, 2013). Insufficient soil moisture impairs fruit yields (Zhang *et al.*, 2017; Hashem *et al.*, 2018; Nemeskéri *et al.*, 2019), making irrigation use crucial in regions with water scarcity. In those same studies, the authors reported that despite the loss of yield, water deficit can improve fruit quality.

Irrigation enables the production of vegetables and fruits in Northeast Brazil, but this production is threatened by water scarcity due to increased consumption and climatic variability, which may be aggravated by climate change. In addition, the growing competition for water resources between agriculture and other sectors is forcing a search for new irrigation strategies (Medyouni *et al.*, 2021), and the available water resources need to be used more efficiently (Bogale; Tesfaye; Geleto, 2016). Studies have been conducted to increase irrigation water productivity (IWP) in different crops (Koech; Langat 2018, Hatfield; Dold, 2019). Among the techniques studied, plastic mulch has been widely used in arid and semiarid regions of China (Wang *et al.*, 2009; Zhao *et al.*, 2012). Plastic mulch can increase IWP by reducing evaporation (not by increasing water in deep layers, but by minimizing surface evaporation), according to Bu *et al.* (2013), Li *et al.* (2013), Liu *et al.* (2014) and Zhang *et al.* (2018). The plastic mulch in drip irrigation cultivation systems can be excellent for not only saving water but also increasing tomato productivity (Biswas *et al.*, 2015).

Studies have found that the use of mulching increases the height of tomato plants (Berihun, 2011; Parmar; Polara; Viradiya, 2013; Pinder *et al.*, 2016), the number and weight of fruits (Pinder *et al.*, 2016), and productivity (Singh; Kamal, 2012; Biswas *et al.*, 2015). In addition, Hudu *et al.* (2002) reported higher yields of tomato with a grass mulching compared to plants without a grass mulching grown in a semiarid region of Nigeria. However, crop responses to irrigation strategies, such as cover and deficit irrigation, are site-specific and highly affected by climatic conditions (Zhang *et al.*, 2017).

In the semiarid region of Brazil, tomato production is predominantly conducted by small producers that do not have substantial technological skills and specific information regarding the improvement of water productivity. Thus, it is necessary to study these production techniques under these environmental conditions because drip-irrigated tomatoes grown in the semiarid region of Brazil can benefit from the use of mulching that will decrease the total water demand without negatively affecting yields. Thus, we tested the validity of the following hypotheses: (i) compared to the control without a mulching, a mulching can reduce soil water loss and improve plant performance with a consequent increase in productivity and tomato fruit quality; (ii) the application of deficient or excess irrigation depths (IDs) impairs yield, fruit quality, and IWP in arid regions of Brazil; and (iii) given the same volume of irrigation deficit, the use of a mulching reduces the loss of tomato plant productivity and increases the IWP. Therefore, the objective of this study was to evaluate the effect of different levels of irrigation and the use of mulching on the productive and quality attributes of tomato fruits grown in the semiarid Northeast Region.

4 MATERIALS AND METHODS

4.1 Experimental site

A field experiment was conducted between October 1, 2018 (sowing), and February 19, 2019 (last harvest), at a commercial farm located in Poções, Bahia state, Northeast Brazil (14°31'47"S, 40°18'06"W, a mean altitude of 760 m). The average annual temperature and rainfall are 19.8°C and 572 mm, respectively. The climate is classified as BSh (hot semiarid climate according to the Köppen-Geiger classification). While a total rainfall of 246 mm was recorded between the end of November and the beginning of December, the reference daily evapotranspiration (ETo) totalled 494 mm for the entire experimental period so that a water deficit condition predominated during the experimental period.

An analysis of soil in the 0-20 cm layers showed the following results: P (resin) = 2 mg dm^{-3}; K^+ (resin) = 0.23 Cmolc; Ca^{2+} = 2.70 Cmolc; Mg^{2+} = 1.80 Cmolc; Al^{2+} = 0.20 Cmolc; H^+ = 5.0 Cmolc; C = 0.23 Cmolc; and CEC = 4.93 Cmolc dm^{-3}. The soil texture was classified as sandy clay (sand: 45.0%, silt: 9.0%, and clay: 46.0%).

The field capacity and permanent wilting point were 0.272 cm^3 cm^{-3} and 0.194 cm^3 cm^{-3}, respectively, which were reached at soil matric potentials of -33 and -1,500 kPa, respectively.

4.2 Experimental design and treatments

The seeds were sown in polystyrene trays 128 cells, each containing the commercial substrate Tropstrato®. Transplantation occurred when the plants reached the stage of 3-4 true leaves. Hybrid tomato cv 'Trucker' seedlings of uniform size at 30 days were transplanted to the field, with a spacing of 0.6 m between plants within the rows and 1.5 m between rows of plants. The experimental field was 504 m^2 (18 m x 28 m) and consisted of 20 plots and 40 subplots (each plot was composed of two subplots). There was an additional 3 m wide traffic corridor between blocks 1 and 2 and blocks 3 and 4. The plastic mulch was black, 25 µm thick, and applied immediately after transplantation.

The treatments consisted of five IDs (305, 440, 495, 610, and 725 mm $cycle^{-1}$) with and without mulching (bare soil). The treatments were delineated in randomized blocks with four replicates and arranged in a split plot design: IDs were assigned to the plots, and treatments with cover/without cover were assigned to the subplots. Each experimental plot consisted of 23 plants (20.7 m^2), and each subplot consisted of a 7.2 m long row containing 12 plants (10.8 m^2). The first and last plants of each subplot were considered borders.

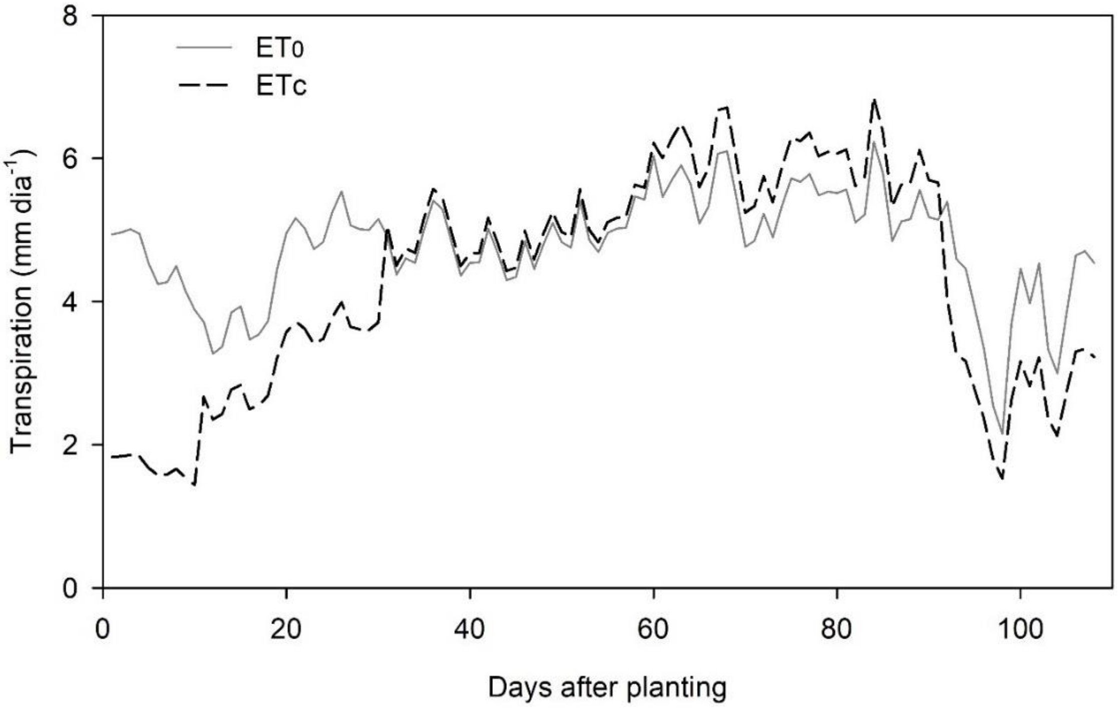
Fertilizer was applied at transplantation at a ratio of 1.0 t ha^{-1} of 4N-14P-8K and 157.2 kg ha^{-1} of P (simple superphosphate). Seven days later, 31.4 kg ha^{-1} of P, simple superphosphate, was applied as a coating. The other fertilizers were applied via fertigation. The conductivity of the fertigation solution measured at the end of the drip line in the initial phase of crop development ranged from 1.0 to 1.5 mS cm^{-1}. For the fruit filling, ripening, and harvesting stages, the CEC solution ranged from 1.75 mS cm^{-1} to 2.5 mS cm^{-1}. The total amounts of fertilizers applied via fertigation per ha for the entire crop cycle were 320.0 kg ha^{-1} N, 156.8 kg ha^{-1} P, 392.4 kg ha^{-1} K, 203.0 kg ha^{-1} S, 176.0 kg ha^{-1} S, 108.0 kg ha^{-1} Mg, 9.0 kg ha^{-1} Mn, 5.0 kg ha^{-1} Zn, and 15.6 kg ha^{-1} B. Despite the different emitter flow rates for each treatment, the fertilizer rate for optimal plant growth was calculated to meet the plants' nutrient demand under the lowest water level. Doses were calibrated for the lowest water depth (305 mm), which could lead to leaching/dilution at higher water depths (610-725 mm), acting as a confounding variable.

4.3 Irrigation management

The ID applied to each treatment via the drip system was obtained with different emitter flow rates: 1.6, 2.3, 2.6, 3.2, and 3.8 L h^{-1}, which corresponded to IDs of 305, 440, 495, 610, and 725 mm $cycle^{-1}$, respectively. The emitters were spaced 0.6 m apart, and the lateral lines were spaced at 1.5 m. From one block to the next, emitters with the same flow rate (plots) were connected to each other by piping without emitters.

The IDs, in mm $cycle^{-1}$, corresponded to 65, 95, 105, 130, and 155% of crop evapotranspiration (ETc). The five ETc replacement rates (65, 95, 105, 130, and 155%) were obtained with Kc values determined by Silva *et al.* (2013). The ETo and the total ETc during the experiment were 495 and 465 mm, respectively; their daily values are shown in Figure 1.

Figure 1. Reference evapotranspiration (ETo) and crop evapotranspiration (ETc) observed during the experiment.



4.4 Measurements

4.4.1 Productive attributes

Tomato fruits were harvested when fully ripened throughout the duration of the experiment. The yield parameters consisted of total yield (TY) per hectare (t ha^{-1}), mean fruit weight (FW) (g), and mean fruit diameter (FD). For the TY, the fresh FW in each experimental unit (10 useful plants) was measured, and we converted the value to the total number of plants per ha. The average FW consisted of the mean values of 10 fruits per harvest (of a total of seven) that were fully ripe and randomly harvested. The mean FD consisted of 10 fruits per harvest (of a total of seven) that were fully ripe and randomly harvested using a 0.01 mm digital calliper.

4.4.2 Irrigation water productivity (IWP)

The IWP estimation was calculated based on the relationship between the TY and the ID applied throughout the cycle (mm). The IWP, expressed as kg ha^{-1} mm^{-1}, was calculated using the formula IWP (kg h^{-1} mm^{-1}) = TY (kg)/ID (mm).

4.4.3 Fruit quality attributes

Fruit quality measurements were performed on 10 fully ripe, randomly harvested fruits per useful plot. Each of the 10 fruits was identical in size and colour, and all were harvested on the same day. The determination of the fruit quality attributes began immediately after harvest.

The firmness of the fruits, described as the maximum penetration force required to rupture the pericarp, expressed in Newtons (N), was measured using a digital penetrometer (TR penetrator, model WA68, Italy) equipped with a cylindrical stainless-steel probe with a point tip 8 mm in diameter. Three measurements, located 120° from each other, were conducted in the equatorial region of each fruit.

After the firmness measurements, five fruits from each experimental unit were ground together in a blender to produce the tomato juice that was used to determine the total acidity (pH), total soluble solids (TSS), and titratable acidity (TA). The pH values were determined instantaneously in tomato juice using a bench pH metre (model MB-10, Mart, São Paulo, Brazil). The TSS content, expressed in °Brix, was determined using a digital refractometer (Model r2 mini REICHERT, USA). For the TA measurements, approximately 20 g of tomato juice was transferred to 50-mL volumetric flasks filled with distilled water to full capacity. A 10 mL aliquot of this solution was then titrated with a NaOH solution (0.05 mol L^{-1}) using phenolphthalein (pH 8.1) as an indicator. The results were expressed as percent citric acid (AOAC International, 1997). The TSS/TA ratio was calculated as a flavour indicator as described by Kader *et al.* (1978).

4.4.4 Growth characteristics

At 73 days after transplantation (DAT), when the plants stopped growing in height, plant height (PH) and stem diameter (SD) were measured. The PH was measured with a tape measure from the base of the stem to the apex. The SD was measured with a digital calliper at 2 cm aboveground.

4.4.5 Data analysis

The data were tested for normality (Lilliefors) and homoscedasticity (Cochran and Bartllet). After ANOVA, mean comparisons for coverage (qualitative factor) were performed using Tukey's test ($p<0.05$); for irrigation depths (quantitative factor), analysis was performed using polynomial regression (linear/quadratic). All statistical analyses were performed using SAEG software (version 9.1) (Ribeiro Júnior, 2001).

5 RESULTS AND DISCUSSION

5.1 Effect of irrigation depth and cover treatments on tomato yield, fruit quality attributes, and growth parameters

In Table 1, the significance of the effects of the bidirectional ANOVA performed for each attribute of productivity, fruit quality, and growth variables was determined. The ID x cover interaction was significant for total fruit acidity (pH) and SD ($p<0.05$). Analysing the isolated effect of the irrigation treatment, we observed a significant effect for the variables TY, FW, FD, IWP, TSS, TSS/TA, SD, and PH. For the source of variation in coverage, there was an isolated effect only for the variables SD and PH.

Table 1. Two-way analysis of variance (ANOVA) for yield, fruit quality and growth traits in tomato.

Traits	Source of variation				
	Irrigation level (IL)	Mulching (M)	IL x M	CV-1 (%)	CV-2 (%)
TY	**	ns	ns	6.42	7.04
FW	**	ns	ns	2.63	3.74
FD	**	ns	ns	1.14	1.03
IWP	**	ns	ns	8.02	7.74
pH	ns	ns	*	1.46	1.00
TSS	*	ns	ns	5.34	3.56
TA	ns	ns	ns	11.85	7.72
TSS/TA	*	ns	ns	13.96	10.57
FF	ns	ns	ns	9.39	14.39
SD	**	**	**	6.81	4.59
PH	**	**	ns	4.41	3.00

Tomato total productivity (TY), average fruit weight (FW), average fruit diameter (FD), water productivity (IWP), total acidity (pH), total soluble solids (TSS) titratable acidity (TA); ratio between total soluble solids and titratable acidity (TSS/TA), fruit firmness (FF), stem diameter (SD) and plant height (PH) affected by different irrigation regimes (IL), use or not of mulching (M) and its interactions. '*', '**', significance level at 0.05 and 0.01, respectively, 'ns' not significant. CV-1 and CV-2, coefficients of variation linked to error 1 and error 2, respectively.

Water constitutes the most critical component of plant tissues, accounting for up to 94% of the fruit mass in tomatoes (Koh Charoenprasert; Mitchell, 2012). It serves as a vital medium for all cellular and biochemical processes, including photosynthesis. Water scarcity triggers a cascade of morphoanatomical, physiological, and biochemical responses aimed at enhancing water use efficiency (Kapoor *et al.*, 2020). However, prolonged water deficit compromises turgor pressure, hindering cell division and plant growth (Dariva *et al.*, 2021). Consequently, a reduction in soil water content predictably diminishes tomato yield.

Tomato is a water-demanding crop, and previous studies have consistently demonstrated yield reductions under water-limited conditions (Chen *et al.*, 2014; Zhang *et al.*, 2017; Hashem *et al.*, 2018). The magnitude of yield loss depends on the severity, duration of stress, and the plant's developmental stage, which in turn influences intrinsic water use efficiency (IWP) (Ghannem *et al.*, 2020). Tomato plants exhibit heightened vulnerability to water stress during flowering and fruiting stages (Keabetswe *et al.*, 2019; Khapte *et al.*, 2019). In the present study, designated irrigation water quantities were applied throughout the entire crop cycle.

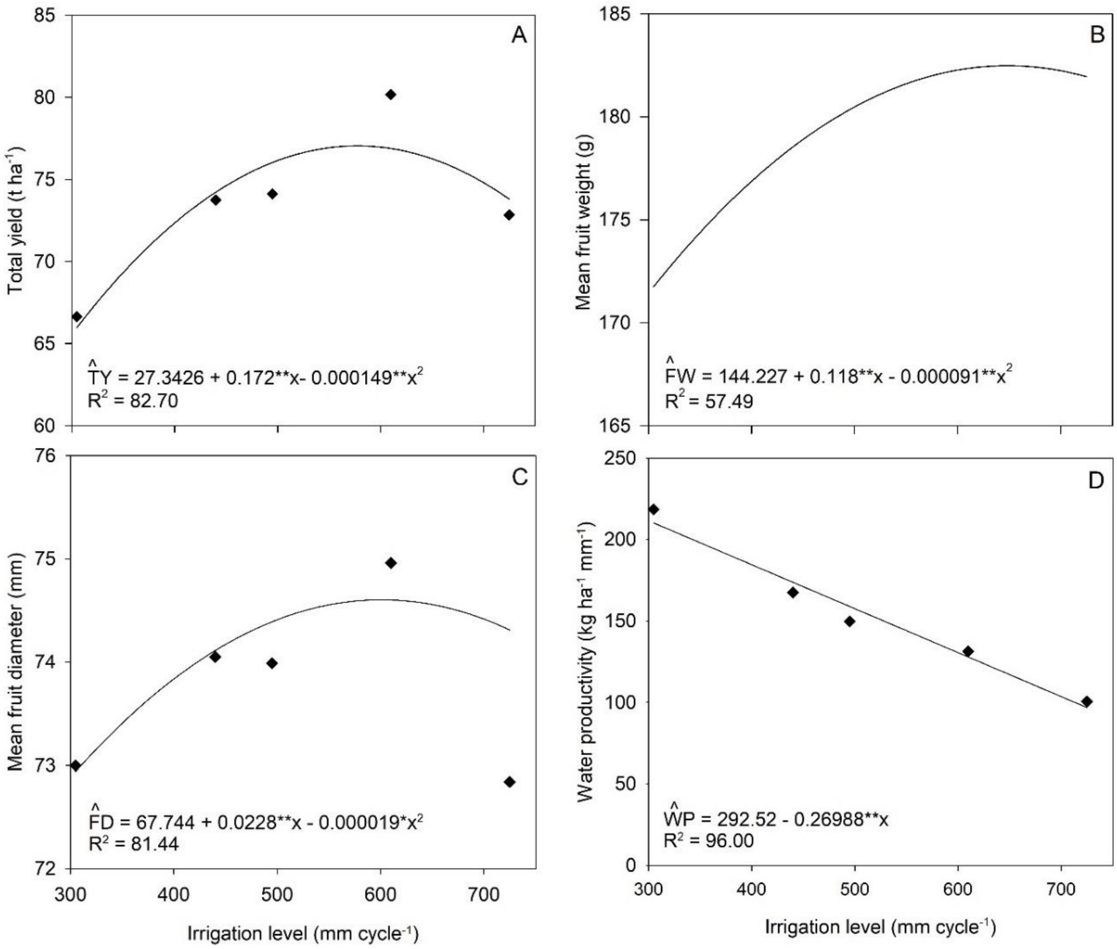
5.2 Productive attributes and water productivity

There was an increasing quadratic adjustment for yield (TY, FW, and FD), which was drastically affected by the irrigation treatment with a lower water depth. A 17% increase in total productivity was observed from the smallest ID applied to the greatest ID applied (66 t ha^{-1} for 305 mm cycle^{-1} to 77 t ha^{-1} for 577 mm cycle^{-1}, respectively), with a consequent reduction (4.3%) in TY up to the greatest ID (74 t ha^{-1} in 725 mm cycle^{-1}) (Fig. 2A). The average FW is a relevant component of tomato production, and from the point of view of commercialization, it can indirectly represent fruit size. The highest mean FW value was observed for the ID that provided

648 mm cycle^{-1}, which was on average 6% higher than that observed for the lowest ID (305 mm cycle^{-1}) (Fig. 2B). A reduction of less than 1% in FW was observed with an increase in water depth applied up to 725 mm cycle^{-1}. The application of the 600 mm cycle^{-1} ID provided a greater mean FD, reaching a value of 75 mm, while the lowest and highest applied ID, 305 and 725 mm cycle^{-1}, recorded mean diameters of 73 and 74 mm, respectively (Fig. 2C).

The IWP as a function of ID was fitted to a linear regression model (r^2 = 96%). A reduction on the order of 46% in the IWP was observed when comparing the IDs from 305 to 725 mm cycle^{-1} (210 kg ha^{-1} mm^{-1} in the 305 mm cycle^{-1} and 97 kg ha^{-1} mm^{-1} in the 725 mm cycle^{-1}) (Fig. 2D). The response of the IWP to the water levels was different from that of the yield, in which the treatment that promoted higher crop yields did not necessarily have a higher IWP. The highest IWP was obtained at the lowest ID, corresponding to 65% of the ETc (305 mm).

Figure 2. Total productivity (A), average fruit weight (B), average fruit diameter (C) and water productivity (D) as a function of different irrigation depths. **, * Significant at the probability level of 0.1 and 0.5, respectively, by the "F" test at 95% confidence interval.



Source: Manoel Nelson de Castro Filho, Poçoes/BA, 2018.

Several studies have documented the detrimental effects of reduced irrigation depths (IDs) on marketable fruit production (Du *et al.*, 2017; Lovelli *et al.*, 2017; Zhang *et al.*, 2017). In this study, the treatment with the lowest applied ID (305 mm cycle^{-1}) yielded the least fruit (66 t ha^{-1}). Notably, while reductions in total yield (PY), mean fruit weight (FW), and fruit dry weight (FD) were observed at lower IDs, similar decreases were also evident when IDs exceeded the optimal level. These findings align with those of Silva *et al.* (2014).

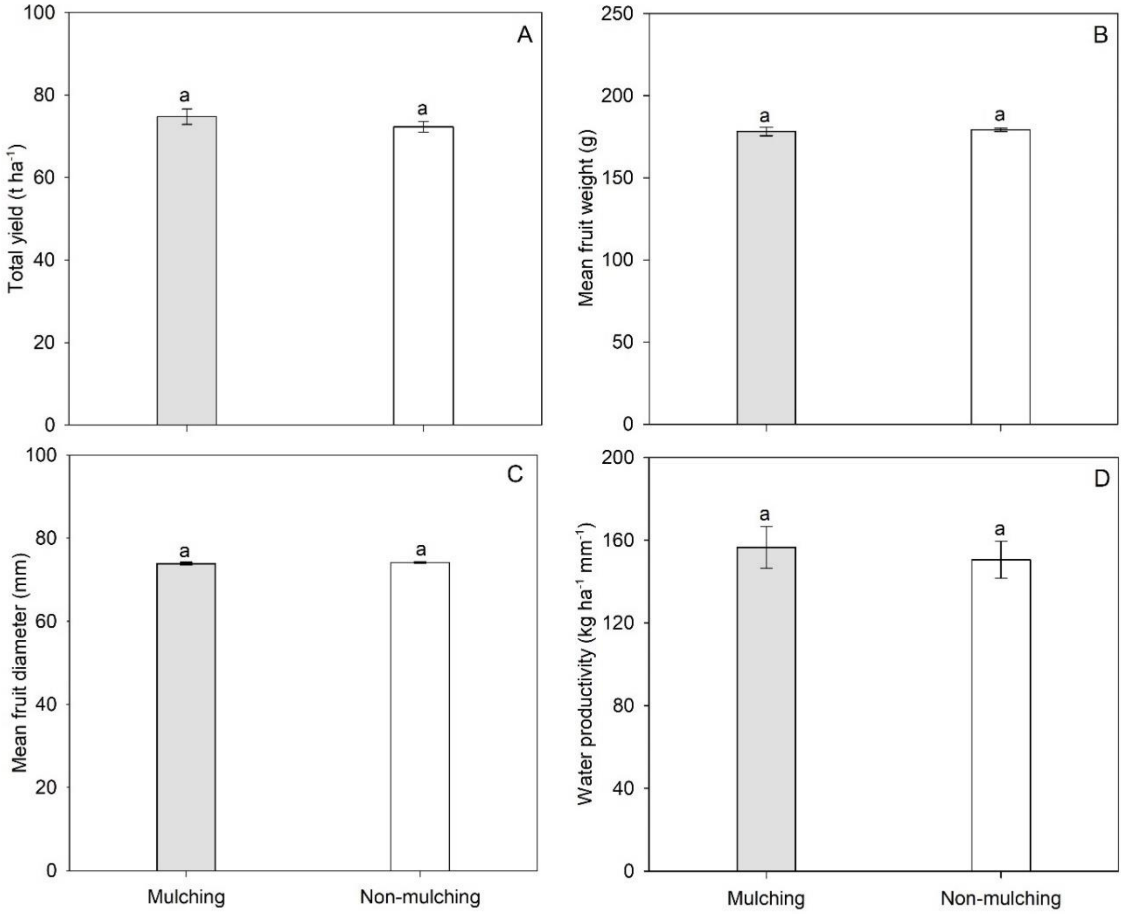
The lower fruit production, FW, and FD observed with the highest IDs can be associated with increased nutrient leaching beyond the root zone. Li *et al.* (2017) reported that fertilizer concentrations remain high under water stress but decrease with frequent and full irrigation. Furthermore, moisture is the primary meteorological factor influencing pest and disease incidence (Fara *et al.*, 2019). High humidity promotes pathogen infectivity, disease development, and pathogen spread (Turkington *et al.*, 2014), potentially impacting crop performance.

Maximum values for yield attributes (TY, FW, and FD) were attained within a range of 577-648 mm cycle^{-1} irrigation depths (ID). Notably, the highest TY was observed at 577 mm cycle^{-1}, the highest FW at 648 mm cycle^{-1}, and the highest FD at 600 mm cycle^{-1}. These findings align with Silva *et al.* (2013), who reported increased fruit number and yield per plant with 100-133% ETc (tomato water consumption) application.

While mild water deficit can enhance tomato water productivity (IWP) (Lu *et al.*, 2019; Nangare *et al.*, 2016), exceeding a certain threshold can severely impact total fruit production (Nangare *et al.*, 2016). In this study, the observed decrease in IWP with increasing ID was less pronounced than the water savings achieved through reduced irrigation. This suggests that crops can tolerate a degree of water deficit with minimal yield loss, leading to significant reductions in irrigation water use, as reported by Cantore *et al.* (2016) and Giuliani *et al.* (2016). The highest IWP (210 kg ha^{-1} mm^{-1}) was achieved with 305 mm cycle^{-1}, corresponding to 65% ETc. This aligns with Zhang *et al.* (2017) who observed higher IWP at 60-80% ETc and Du *et al.* (2017) who reported a peak IWP at 50% ETc. Similarly, Campos *et al.* (2009) found no significant yield reduction in water-stressed tomato plants, resulting in increased IWP compared to well-irrigated controls. Furthermore, Lovelli *et al.* (2017) demonstrated that early-fruit-ripening irrigation cessation does not affect yield but boosts IWP. Therefore, if ID reduction has minimal impact on fruit production, IWP is expected to increase.

The use of mulching did not have a significant effect on the productive attributes of the tomato plant or the water productivity ($p > 0.05$) (Fig. 3A-D). Although not significantly different, higher numerical values were observed in the total productivity and IWP in the treatment with mulching. While the average total yield was 73.5 t ha^{-1}; the average TY was 73.5, the TY was 75 t ha^{-1} in the treatments with mulching and 72 t ha^{-1} in the treatments without mulching (Fig. 3A), and the water productivity was 156 kg ha^{-1} mm^{-1} with a mulching and 150 kg ha^{-1} mm^{-1} without a mulching (Fig. 3D).

Figure 3. Mean values of total yield (A), mean fruit weight (B), mean fruit diameter (C) and water yield (D) in plants maintained with mulching and without mulching. The same lowercase letters indicate that treatment with and without mulching did not differ by the F test (p>0.05). Data are expressed as mean ± standard error (n=20).



Source: Manoel Nelson de Castro Filho, Poçoes/BA, 2018.

Biswas *et al.* (2015) reported that combining drip irrigation with mulch can enhance tomato productivity while minimizing water use. This improvement likely stems from the altered microclimate above and below the soil surface created by mulching (Ansary *et al.*, 2017). In our study, while the mulching treatment did not statistically affect yield parameters, a numerically higher total fruit yield (4%) and irrigation water productivity were observed. This could be attributed to increased soil temperature and moisture due to mulching, as reported by Filipović *et al.* (2016) and Zhang *et al.* (2019). Mendonça *et al.* (2021) also observed positive effects on yield and fruit number with green plastic mulch. Additionally, Campagnol *et al.* (2014) found increased water productivity with reduced irrigation in mulched plants compared to unmulched ones. However, it is crucial to note that the response of crops to irrigation strategies like mulching can vary depending on soil and climatic conditions (Zhang, 2017; Mendonça *et al.*, 2021).

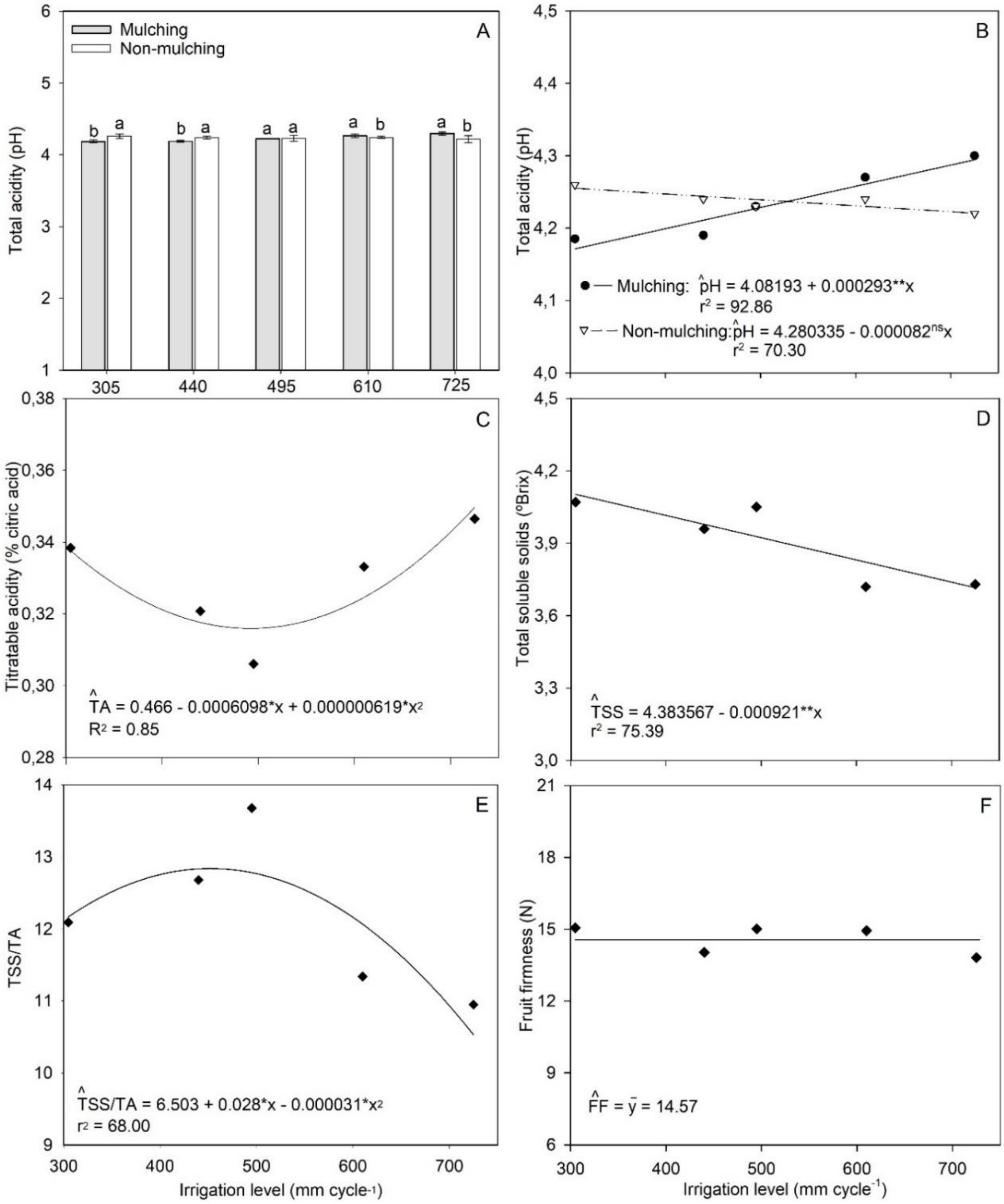
Although several studies have reported positive effects of mulching on tomato yield and water productivity, these benefits were not statistically significant under the conditions of the present study. The main advantage of mulching is the reduction of soil evaporation, which helps maintain higher soil water availability, especially under dry conditions. However, during the experimental period, a rainfall event totalling 246 mm occurred between late November and early December. Considering the clayey sandy loam soil of the experimental area, this rainfall was sufficient to maintain high soil moisture in both mulched and bare soil treatments for a substantial portion of the crop cycle. Consequently, soil water availability was likely similar between treatments, reducing the potential advantage of mulching in conserving water. Under these conditions, the beneficial effects of mulch on evaporation control were minimized, explaining why only numerical increases in yield and irrigation water productivity were observed rather than statistically significant differences. These findings reinforce that the effectiveness of mulching depends strongly on rainfall distribution, soil texture, and the duration of periods without precipitation.

5.3 Effect of irrigation depth and mulching treatment on tomato quality

Figure 4 shows the means of the fruit quality attributes, including total acidity (pH), TSS, TA, TSS/TA, and fruit firmness (FF). The ID × M interaction was significant for total acidity (pH) (Table 1). The pH of the fruits from plants grown with a mulching and irrigated at 305 and 440 mm cycle^{-1} was statistically lower than the pH of the fruits grown from plants without a mulching (4.18 and 4.19 with a mulching and 4.26 and 4.24 a without mulching at 305 and 440 mm cycle^{-1}, respectively) (Fig. 4A). Inverse behaviour was observed at IDs of 610 and 725 mm cycle^{-1}, in which plants are grown with mulching produced fruits with higher pH values. We did not observe significant results for plants to which 495 mm cycle^{-1} was applied (Figure 4A). The pH of the fruits as a function of ID was adjusted to an increasing linear regression model (r^2 = 70.30%) (Fig. 4B). An increase of approximately 3% in pH was observed when comparing the IDs from 305 to 725 mm cycle^{-1} (4.17 in 305 mm cycle^{-1} and 4.29 in 725 mm cycle^{-1}).

There was a decreasing quadratic fit for TA, with a lower value (0.32% citric acid) found when 493 mm cycle^{-1} was supplied (Fig. 4C). The highest TA values were found when low a ID (0.34% citric acid at 305 mm cycle^{-1}) and high ID (0.35% citric acid at 725 mm cycle^{-1}) were applied. The TSS content, which represents the total of all dissolved solids, such as sugar, salts, proteins and acids, showed a decreasing linear regression fit (p <0.05), with a reduction of 11% of the smallest value at the greatest ID applied (4.10 °Brix at 305 mm cycle^{-1} and 3.70 °Brix at 725 mm cycle^{-1}) (Fig. 4D). The TSS/TA ratio showed an increasing quadratic fit, with a maximum of 452 mm cycle^{-1}, equivalent to a TSS/TA ratio of 13°Brix/% citric acid. Linear adjustments with moderate R^2 (pH, R^2=0.70) and high CV in qualitative traits (TSS/TA: 13-14%) reflect inherent biological variability, influenced by microclimates and phenological stages (Fig. 4E). The lowest TSS/TA ratio (10.5°Brix) was estimated at 725 mm cycle^{-1}. For FF, among the regression models tested, there was no significant fit (p> 0.05), with a mean value of 14.57 N (Fig. 4F).

Figure 4. Total acidity (pH) of fruits from plants grown with and without mulching at different irrigation levels (A); estimate of the total acidity of fruits harvested from plants grown in different water regimes within each cover treatment (B) and, titratable acidity (C), total soluble solids (D), TSS/TA ratio (E) and fruit firmness (F) depending on the different irrigation depths. In figure 'A' the same lowercase letters indicate that the cover treatments did not differ among themselves by the Tukey test (p>0.05) at each irrigation level and the bars indicate the standard errors of the mean (n=4). In figures 'b-f', **, * significant at the probability level of 0.01 and 0.05, by the "F" test, respectively.

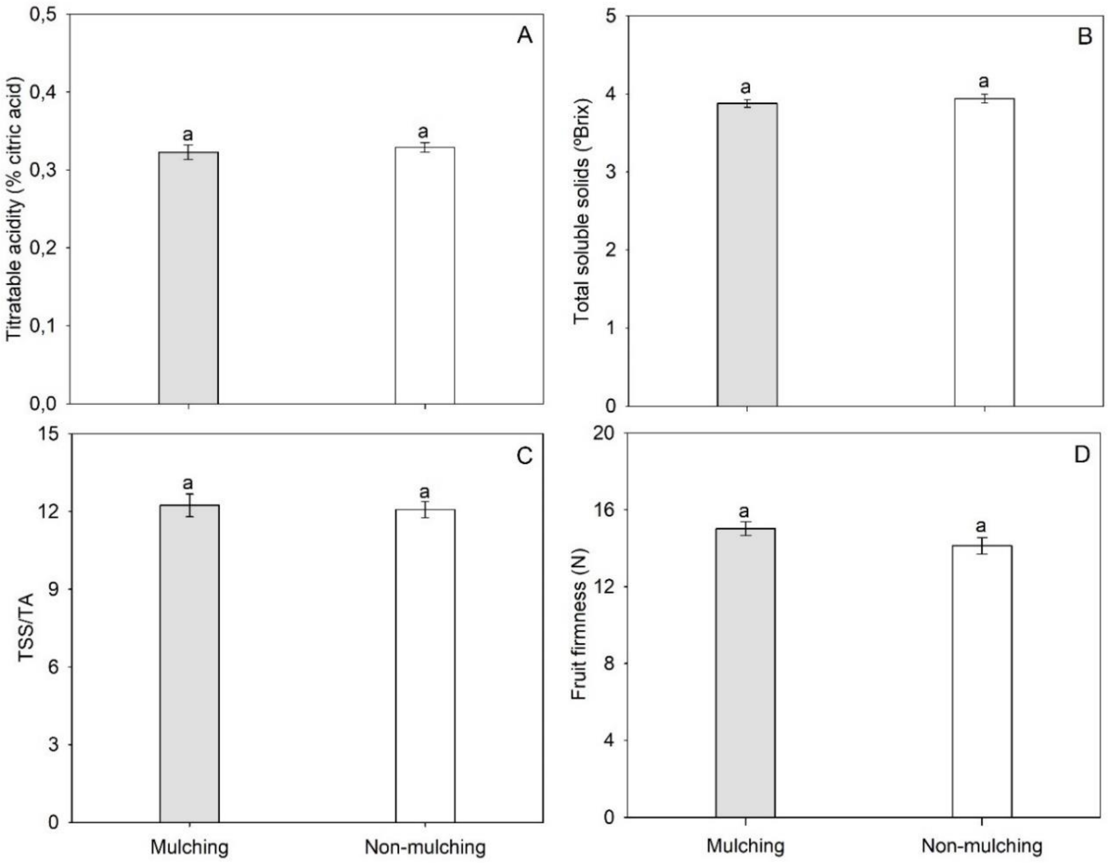


Source: Manoel Nelson de Castro Filho, Poçoes/BA, 2018.

Regarding the productive aspects, the source of variation from cover alone did not have a significant effect on the quality attributes of the tomato plant (p> 0.05) (Fig. 5A-D). Even though with a cover and without a cover did not result in significant differences, the use of a mulching increased the TSS/TA by 2% (mean of 12.2 with a mulching and 12.0 a without mulching) (Fig. 5C) and FF by 7% (15 N with a mulching and 14 N without a mulching) (Fig. 5D).

Although mulching did not significantly affect fruit firmness (FF), the average value observed (14.57 N) indicates that the fruits maintained adequate texture for fresh-market commercialization. Fruit firmness is a key quality attribute related to consumer acceptance, transport resistance, and postharvest shelf life (Batu, 2004; Pinheiro *et al.*, 2016). Tomatoes harvested at commercial maturity generally present firmness values ranging from 10 to 25 N, depending on cultivar, ripening stage, and evaluation methodology (Pinheiro *et al.*, 2016). Therefore, the firmness observed in the present study falls within the expected commercial range, indicating that the fruits were not excessively soft. The absence of differences between mulched and bare soil treatments suggests that the rainfall during the crop cycle reduced differences in soil water availability, preventing the water stress typically associated with increased fruit firmness.

Figure 5. Mean values of titratable acidity (A), total soluble solids (B), TSS/TA ratio (C) and fruit firmness (D) in plants maintained with and without mulching. The same lowercase letters indicate that treatments with and without mulching did not differ by the F test (p>0.05). Data are expressed as mean ± standard error (n=20).



Source: Manoel Nelson de Castro Filho, Poçoes/BA, 2018.

While water depths below 577 mm negatively impacted tomato yield, fruit quality exhibited the opposite trend. Reduced pH values increased total soluble solids (TSS), titratable acidity (TA), and TSS/TA ratio were observed under water deficit (Lovelli *et al.*, 2017; Hashem *et al.*, 2018). This likely occurred due to reduced water content in the fruit, leading to higher concentrations of TSS and acids (Radović *et al.*, 2019; Tang *et al.*, 2010). Our study confirms this, demonstrating increased acidity (lower pH and higher TA) in fruits under water deficit, particularly in smaller irrigation depths. Similar responses were observed with excessive irrigation, which reduces soil aeration and root respiration, hindering water uptake.

Both excessive and insufficient soil moisture impacted fruit pH and TA. These conditions negatively affect gas exchange and carbohydrate synthesis, potentially leading to increased degradation of organic acids into sugars (Halinska; Frenkel, 1991; Karlen *et al.*, 1983). Soares *et al.,* (2012) also reported decreased fruit pH under reduced irrigation. Water deficit induces metabolic changes, including the synthesis of antioxidant compounds like vitamin C and carotenoids (Medyouni *et al.*, 2021) to mitigate the harmful effects of reactive oxygen species (ROS).

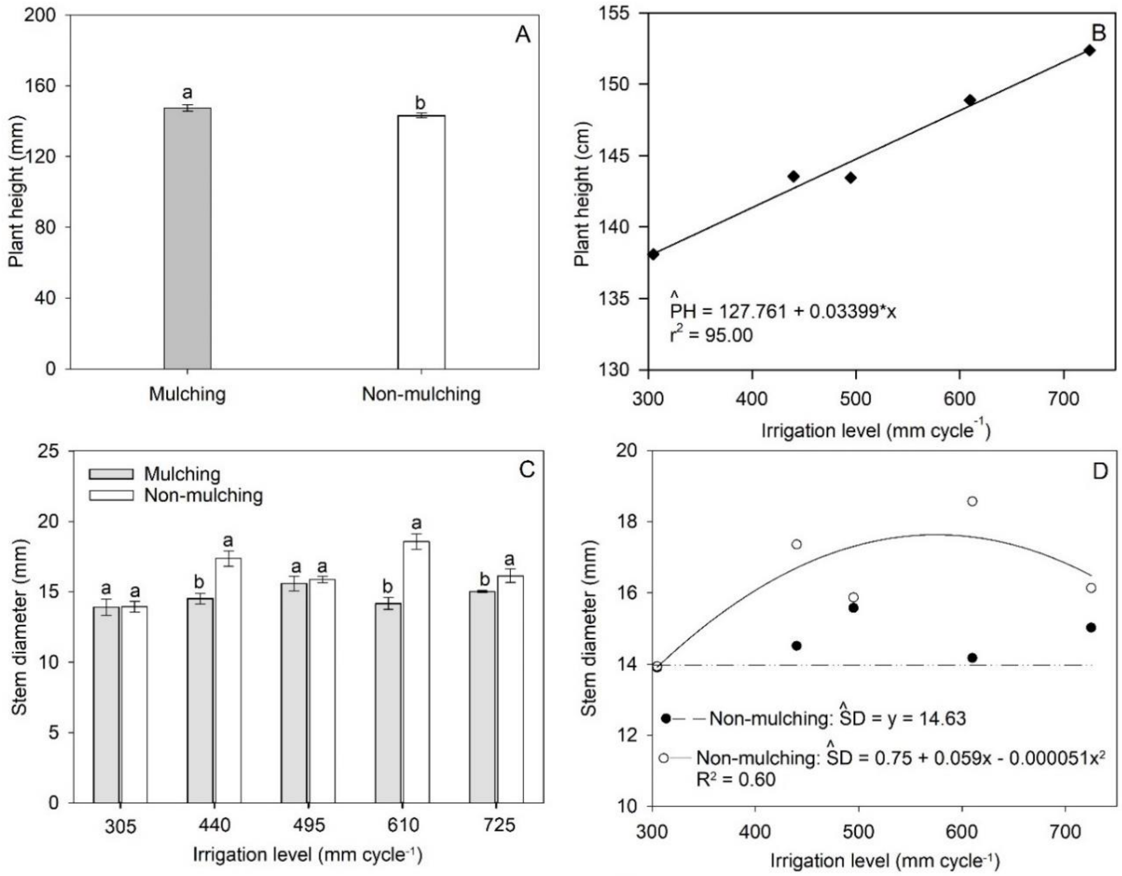
TSS levels indicate fruit sweetness and maturity (Vieira *et al.*, 2014). They influence flavour, nutritional value, and firmness (Hao *et al.*, 2013). In this study, TSS increased with decreasing irrigation depth, consistent with findings by Kuscu *et al.* (2014), and Hashem *et al.* (2018). Fruit firmness (FF) is crucial for fresh consumption. Consumers prefer firm, non-deforming fruits (Ferreira *et al.*, 2010). Firmer tomatoes tolerate long-distance transport without pericarp rupture. In our study, FF remained unaffected by irrigation depth, aligning with Zhang *et al.* (2017) and Agbemafle *et al.* (2014).

Mulching did not significantly affect FF, TA, TSS, or TSS/TA. This aligns with Mendonça *et al.* (2021) who found no significant impact of soil cover on tomato fruit quality. Similarly, Campagnol *et al.* (2014) reported no effect of soil cover on TA. While statistically insignificant, fruits under mulching exhibited slightly higher TSS/TA (2%) and firmness (7%).

5.4 Growth parameters

PH was significantly affected by ID and mulching individually ($p < 0.05$) (Table 1). An increase of 3% in PH was observed with the use of mulching (Fig. 6A). Regarding the IDs, a linear increase was observed with increasing IDs. An increase of 10.33% was recorded from 305 to 725 mm cycle^{-1} (Fig. 6B). In contrast, the SD experienced a significant effect from the I × M interaction. The SD was lower in plants grown with mulching and irrigated with 440, 610, and 725 mm cycle^{-1} than in plants grown without mulching with the same IDs (Fig. 6C). The SD response as a function of the IDs for the plants grown without mulching was fitted to a quadratic model with the largest diameter (17.63 mm) found when applying an ID of 575.04 mm cycle^{-1} (Fig. 6D). Conversely, the SD response in plants grown with mulching could not be adjusted to the IDs, with a mean value of 14.63 mm.

Figure 6. Mean values of plant height with and without mulching (A) and estimate of plant height as a function of different irrigation depths (B); mean stem diameter with and without mulching at different irrigation levels (C) and estimate of stem diameter at different irrigation depths within each cover treatment (D). In figure 'A', the different lowercase letters indicate that the treatment with and without mulching differ by the F test (p>0.05). In figures 'B' and 'D', **, * significant at the probability level of 0.01 and 0.05, by the "F" test, respectively. In figure 'c' the same lowercase letters indicate that the cover treatments did not differ from each other by the Tukey test (p>0.05) at each irrigation level and the bars indicate the standard errors.



Source: Manoel Nelson de Castro Filho, Poçoes/BA, 2018.

A mulching layer helps maintain soil humidity by minimizing evaporation (Bu *et al.*, 2013; Li *et al.*, 2013). This, in turn, alleviates water stress and promotes vegetative growth. Our findings align with existing literature, showing that mulching generally increases plant PH compared to unmulched control groups (Berihun 2011; Parmar; Polara; Viradiya, 2013; Pinder *et al.*, 2016). Additionally, mulched plants displayed a lower average SD, reflecting a more consistent internal microclimate and reduced stress response. This trend is consistent with tomato plants grown under rice straw mulch (Moursy; Mostafa; Solieman, 2015; Mendonça *et al.*, 2021).

Increasing IDs led to a linear rise in tomato plant PH, corroborating results from Agbna *et al.* (2017). However, contrasting findings were reported by Sibomana; Aguyoh; Opiyo, (2013), who observed plant stunting only under severe drought conditions (60% lower irrigation compared to the control).

6 CONCLUSION

The mulching did not significantly affect the attributes of tomato yield and water productivity, and of the quality variables, only the pH improved with the use a cover. Despite the nonsignificant results, slightly higher numerical values (~4%), but without significance (p>0.05). There was no effect of plastic mulch on yield. In addition, the plastic mulch promoted an increase in PH and a decrease in SD.

Optimal irrigation depth of 577 mm (~124% ETc) maximized TY; for IWP, 305 mm (65% ETc). Therefore, considering the results of the present study, plastic mulching did not significantly affect productivity or quality (p>0.05), likely due to the 246 mm rainfall. 577 mm cycle^{-1} (~124% ETc) is recommended for maximum yield under semi-arid conditions in Bahia; future studies should test mulching in dry cycles.

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