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IRRIGATION MANAGEMENT AND BIODEGRADABLE MULCHING IMPACT ON CARROT BIOMETRIC CHARACTERISTICS AND YIELD

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KEYWORDS

Daucus carota L., water depth, soil cover, biodegradable paper, plastic mulching.

ABSTRACT

This study aimed to evaluate the biometric and productive characteristics of carrot (*Daucus carota* L.) under different irrigation levels and soil covers. Experiments were carried out at the Federal University of Viçosa in 2019 and 2020, to evaluate the effect of five irrigation levels (20, 40, 60, 80, and 100% of the daily irrigation depth) and soil coverings (control, plastic mulching, and paper mulching), on the variables soil moisture (U), actual water consumption (AWC), root length (R) and diameter (D), leaf height (H) and temperature (T), normalized difference vegetation index (NDVI), yield (Y) and dry root biomass (DB). Irrigation management was performed with tensiometers. There was no significant interaction ($P < 0.05$) between the factors. Irrigation significantly influenced D, H, T, NDVI, Y, and DB, while the soil cover treatment affected R, D, H, NDVI, Y, and DB. The highest yields were found in 100% irrigation (34.89 t ha^{-1}) and with paper mulching (30.55 t ha^{-1}). The results can guide future adaptations to the carrot production system currently in force in Brazil. As for biometric characteristics, yield, and sustainability in the use of water for irrigation were studied.

INTRODUCTION

Carrot (*Daucus carota* L.) is a vegetable of high economic importance, which contributes to the socioeconomic development of farmers (Carvalho et al. 2016). Carrots are widely consumed in the world due to their dietary benefits, such as providing pro-vitamin A (Titcomb et al., 2019). In Brazil, in 2022, the planted area of carrots in the summer crop was estimated at 8,000 hectares, with an increase in the cultivated area (Cepea, 2021). In Minas Gerais, statistics indicate that the area destined for the production of carrots will be around 5,100 hectares, with record prices per unit, in 2022 (Cepea, 2021).

One way to increase the production per unit of crop area is to manage the available water resources in the field through irrigation (Souza et al., 2020) while maintaining the sustainability of the agroecological system and positive net income. However, according to Carvalho et al. (2016) and Lucian et al. (2019), the carrot crop is directly influenced by irrigation, as it has lower yields when submitted to irrigation depths lower than the consumption demand. In this sense, as future climate scenarios indicate water scarcity and population increase (Liu et al. 2017), strategies are needed to reduce the irrigation depth with less loss of carrot yield.

One of the strategies used by producers is the use of soil mulch (Dlamini et al. 2017). According to Zhang et al. (2020), irrigation when associated with mulching can result in increased water yield in the field, reduced soil evaporation, and soil moisture conservation.

Polyethylene plastic cover, for example, is widely applied to conserve soil moisture (Marí et al. 2019; Zhang et al. 2019b). Nonetheless, while plastic mulching is efficient in improving the uniformity of water and nutrient distribution (Zhang et al. 2019b; Henrique et al., 2021), as well as in the control of weeds (Zhang et al. 2019a), on the other hand, this material generates residues due to the slow degradation in the environment, which requires the removal and management of residues from the cover to recover the area after harvest (Hayes et al., 2019; Marí et al. 2019). Therefore, we seek to replace the use of polyethylene plastic mulching in the agricultural area with sustainable options.

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Among the sustainable options available, biodegradable paper mulch is an alternative to plastic mulch for agroecosystems (Li et al., 2013). Zhang et al. (2019b) and Hayes et al. (2019) indicate that biodegradable polymers have as high an agronomic performance as plastic mulching. Nevertheless, research is needed on the effects of low-cost biodegradable materials on changes in microclimate, soil biotics and fertility, plant growth, and crop yield (Kader et al. 2017; Henrique et al., 2021), especially for carrot, whose cultivation with this technique in Brazil is still underexplored.

In the case of carrots, as the application of the paper and plastic mulch technique is still recent, there are few studies on its development and production when subjected to water deficits, especially in Minas Gerais, a region that is among the most productive in Brazil (Cepea, 2021).

Farmers in the Forest Zone of Minas Gerais State, whose agricultural exploitation led to the replacement of a large part of the Atlantic Forest Biome with areas of coffee, pastures, and horticulture, face problems of soil degradation, reduced production, and decline in biodiversity (Souza et al., 2012; Lopes et al. 2020). Solar incidence in degraded regions influences the temperature, evaporation, and distribution of water in the soil and, therefore, the physical, chemical, and biological properties of the soil (Owuor et al., 2018). Thus, requires soil and water conservation and management practices, such as irrigation and soil cover.

Considering the importance of expanding studies on the association of mulch and irrigation management to produce carrots, this study aimed to evaluate the biometric and productive characteristics of carrots (*D. carota* L.) under different irrigation levels and soil covers.

MATERIAL AND METHODS

Study area

Field experiments were carried out from August to October 2019 (first cycle), and from March to May 2020 (second cycle) in the experimental area of Irrigation and Drainage, of the Agricultural Engineering Department of the Federal University of Viçosa (UFV), Viçosa-MG, Brazil, of which the geographical coordinates are 20°46′9" S, 42°51'43" W, with an elevation of 651 m.

The climate of the region according to the Köppen climate classification is Cwa, humid subtropical with dry winters and hot summers (Souza et al., 2020). The soil of the experimental area was classified as Red-Yellow Argisol (Santos, 2018), and its chemicals and physical characteristics are shown in Tables 1 and 2.

TABLE 1. Chemicals characteristics in the experimental area of Irrigation and Drainage, of the Department of Agricultural Engineering of the Federal University of Viçosa (UFV) during the first (2019) and second cycle (2020), at the soil depth of 20 cm.

Year	pH	Ca	Mg	Al	P	K	H+Al	SB	CTC	V
	H_2O	$cmol.dm^{-3}$			$mg.dm^{-3}$		$Cmol_c.dm^{-3}$			%
2019	5.69	3.90	0.77	0.00	19.20	60	3.2	4.01	7.21	55.6
2020	5.62	2.84	0.65	0.00	14.20	35	2.9	3.58	6.48	55.3

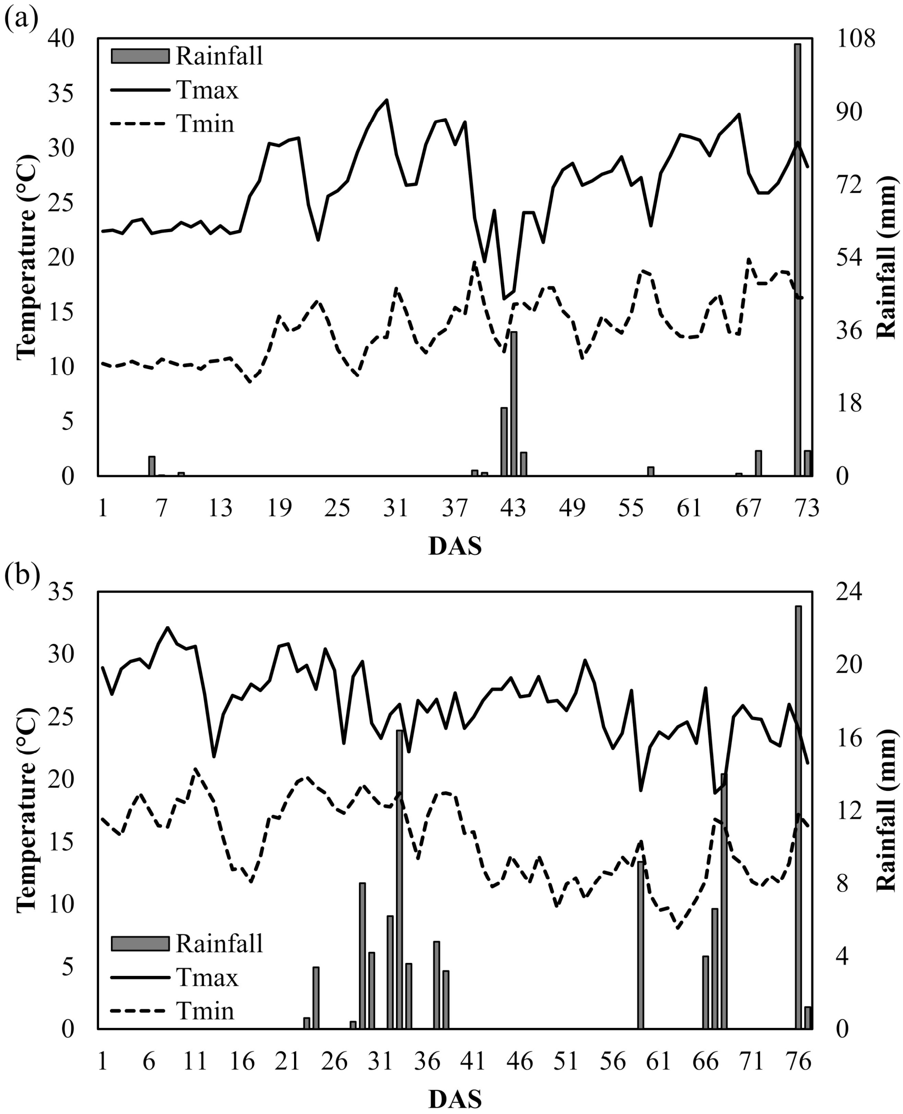
Legend: P, K available extracted with Mehlich I; exchangeable Ca^{+2}, Mg^{+2} and Al^{+3} extracted with 1 mol L^{-1} KCl; H + Al - calcium acetate extractor 0.5 mol L^{-1} - pH 7.0; SB - base saturation; CTC - cation exchange capacity at pH 7.0; V- base saturation index; P-rem - remaining phosphorus.

TABLE 2. Soil physical characteristics in the experimental area of Irrigation and Drainage, of the Department of Agricultural Engineering of the Federal University of Viçosa (UFV).

Soil Depth (cm)	Texture	B.D. (g/cm³)	θ_{FC} (cm^{-3} cm^{-3})	θ_{PW} (cm^{-3} cm^{-3})
0–20	Sandy clay	1.30	0.48	0.25
20–40	Sandy clay	1.20	0.51	0.26

Legend: B.D. is the bulk density, θFC is the field capacity (−10 kPa), and θPW is the permanent wilting point (−1500 kPa).

During the experiments, the mean maximum and minimum air temperatures were 26.67 and 13.50 °C (first cycle), and between 26.18 and 15.00 °C (second cycle), respectively. The accumulated rainfall for 2019 and 2020 was 188.0 and 109 mm, respectively (Fig. 1).



Legend: Days after sowing (DAS); Rainfall, mm (▬); Maximum temperature, °C (- - - Tmax); Minimum temperature, °C (—— Tmin).

FIGURE 1. Maximum (Tmax) and minimum (Tmin) temperature in °C, and rainfall (mm) during the carrot growing period in 2019 (a) and 2020 (b) in Viçosa-MG

Experimental design

The experiments were carried out in a 5 × 3 factorial scheme, with five irrigation levels (20, 40, 60, 80, and 100% of the daily irrigation depth) and soil coverings (control, plastic mulching, and paper mulching). To respect the basic principles of experimentation (repetition, randomization, and local control) a randomized block design with four replications was used. Each experimental plot consisted of three rows of plants spaced at 0.3 m and 0.1 m between plants, containing 30 plants (0.9 m^2).

Agronomic practices

The experiments were carried out in an area of 84 m^2. Soil preparation was carried out with plows seven days before sowing. The fertilization was carried out before seeding, using the using the fertilization recommendation of the State of Minas Gerais, described by Ribeiro et al. (1999), according to the interpretation of the chemical analysis of the soil, 14.4 kg of formulated fertilizer 4-14-8 (NPK) and supplementation with urea (982 g) and potassium chloride (331 g) were applied.

The carrot cultivar used was 'Brasília' (Embrapa Hortaliças - CNPH, Brasília, DF), as it presents field resistance to leaf spot (Luz et al. 2009), and the seeds are widely traded in the region. Manual sowing was carried out using 3 seeds per hole at 0.01 m depth. After the establishment of the culture, when 0.10 m in height and 25 days after germination, the plants were thinned, and the treatments started with irrigation and mulching in the soil.

Weeds were controlled by manual weeding performed weekly to remove *Oxalis tetraphylla* and *Cyperus rotundus* until harvest. There was a recurrence of *Diabrotica speciosa*; therefore, in 2019, physical control was carried out for population control. In the same year, there was an occurrence of *Cercospora carotae*, and for control, two sprays were carried out, with fungicide.

Management and irrigation system

A surface drip irrigation system was used. This comprises a 16 mm drip tape (Toro, model Aqua - Traxx, Plentirain, China) with emitters spaced every 0.30 m and a flow rate of 1.50 L h^{-1} with an operating pressure of 1 bar. A drip tape was allocated to each plant row. After sowing, 30 mm of water was applied during the germination phase until thinning.

Irrigation management was performed by tensiometers installed in each treatment, at depths of 0.10 m and 0.30 m. Tensiometers were read daily with the aid of a digital tensimeter between 8 am and 10 am. The tension reading of the tensiometers was converted into soil moisture through the soil water method curve and provided by the Richards chamber. The van Genuchten model (van Genuchten, 1980) was adopted, considering the hydraulic characteristics of the soil in table 2.

Equation 1 was used to calculate the daily irrigation depths (20, 40, 60, 80, and 100%) for each treatment. To apply the irrigation depth, we used the values of 0.2 (corresponding to 20%), 0.4 (40%), 0.6 (60%), 0.8 (80%), and 1.0 (100 %). The criterion for choosing the irrigation depths was Soil water depletion fraction for no stress (p) (Mantovani et al. 2009).

$$ID = ((\theta FC - \theta a) * da * Z * def)/Ef \quad (1)$$

in which:

ID is the irrigation depth, mm;

θFC - volumetric soil moisture at field capacity, $m^3\ m^{-3}$;

θa - soil moisture before irrigation, $m^3\ m^{-3}$;

da - apparent density of the soil, g cm^{-3}; Z is the depth of the crop root system, mm;

def - percentage of deficit applied, %,

and Ef - efficiency of drip irrigation system, %.

For visualization and discussion, the variation in soil moisture was quantified in the temporal scale of 30, 35, 40, 45, 50, 55, 60, and 65 DAS (days after sowing) and presented in the results.

Actual water consumption

Actual water consumption (AWC) during the carrot cycle was calculated based on the soil water balance through [eq. (2)].

$$AWC = I + P + Cr - Rf - Dp \pm \Delta S \quad (2)$$

in which:

AWC - actual water consumption, mm;

I - applied irrigation, mm;

P - rainfall, mm;

Cr - capillary rise, mm;

Dp - percolation, mm;

Rf - runoff, mm,

ΔS - change in soil-water storage between sowing and harvesting, mm.

In [eq. (2)], Cr was considered null because the water table was more than 15 m below the surface, Rf was also assumed to be insignificant because the experimental area is flat, and Dp was significant only when there was precipitation.

Mulching

Plastic and paper mulching were used to cover the soil. The plastic mulching had a thickness of 22 µm and a weight of 15 g m^{-2}. The paper mulching had a thickness of 80 µm and a weight of 80 g m^{-2}. Holes with diameters of 50 mm were made for the plant to pass through the covers.

Evaluated variables

The harvest was carried out on October 26, 2019, for the first cycle and May 25, 2020, for the second cycle. The evaluations were carried out in the five plants of the central line of each experimental plot.

With the plant still in the soil, they were measured on the day of harvest for leaf height (H), index of normalized difference vegetation (NDVI), and temperature leaf (T). The heights of the carrot leaves were measured from the root neck to the leaf apex with a millimeter's ruler. The NDVI was measured using a GreenSeeker handheld crop sensor (NTech Industries Inc., Ukiah, CA), passing through the plants at a height of 0.60 m from the canopy (Henrique et al., 2021). Leaf temperature was projected using a digital infrared thermometer with a laser sight, model ST600, from INCOTERM® (accuracy of ± 2.0 °C and resolution of 0.1 °C). During the readings, the device was positioned 0.15 m away from the leaves (Jackson, 1982).

Subsequently, the plants were harvested, washed, and sanitized, and they were separated from the leaves for the total quantification of the root matter with the aid of an analytical digital balance with a resolution of 0.01 g. Then, the carrot root length (R) was measured with the aid of a millimeter ruler, starting from the carrot neck to the root apex. The root diameter (D) was measured on the upper diameter with a digital caliper, reading in millimeters.

For the percentage of root dry biomass (DB), the roots were dried at 65 °C for 72 h in a forced air circulation oven. The root yield (Y) estimate was calculated in one hectare containing 300,000 plants.

Statistical analysis

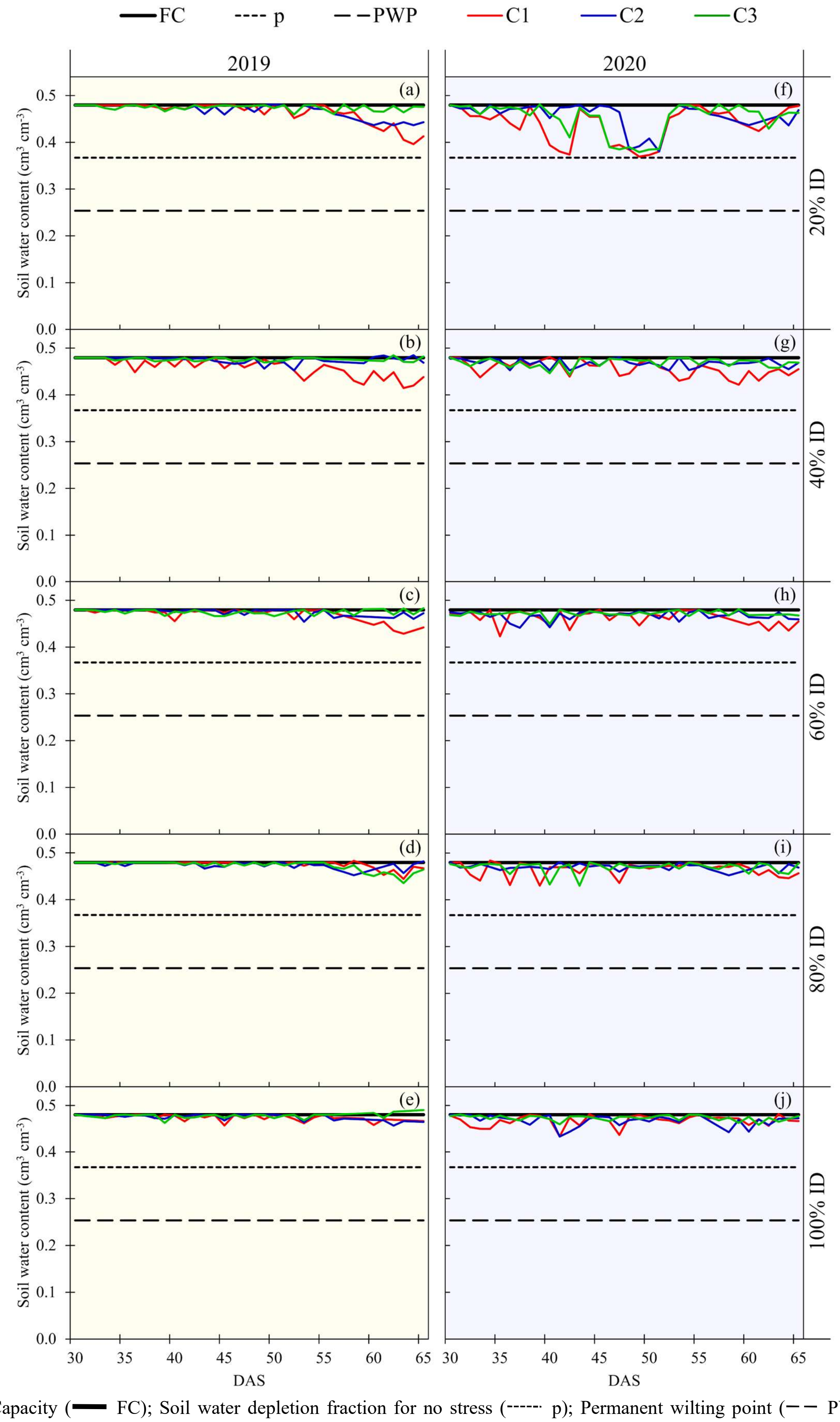
Data were submitted for analysis of variance and regression using R software (R Core Team, 2020) and ExpDes package, version 1.2.2 (Ferreira et al., 2014). For the qualitative factor, the means were compared using the Tukey test, adopting a probability level of 5%. For the quantitative factor, the models were chosen based on the significance of the regression coefficients, the coefficient of determination, and the behavior of the phenomenon under study.

RESULTS AND DISCUSSION

Soil moisture variation

The variation of the average moisture in the 0.30 m soil depth layer, for the irrigation depths and soil cover, is presented in Fig. 2. There were variations in the amounts of water in the profile with the increase in the irrigation deficit along the cycles.

In irrigation with a deficit of 20% of the irrigation depth (20% ID), the variation of soil moisture was between 0.39 (first cycle) and 0.32 (second cycle) to 0.48 $cm^3\ cm^{-3}$, reaching the field capacity of the soil (Table 2). With an irrigation deficit of 40% ID, the water volumes varied from 0.41 to 0.48 $cm^3\ cm^{-3}$ in both years of study (first and second cycles). For a 60% deficit of irrigation, the water content in the profile varied between 0.42 and 0.48 cm $cm^3\ cm^{-3}$ (first and second cycles).



Legend: Field Capacity (▬ FC); Soil water depletion fraction for no stress (------ p); Permanent wilting point (— — PWP). Days after sowing (DAS); irrigation levels: 20, 40, 60, 80, and 100% of the daily irrigation depth (ID); control (—— C1), plastic mulching (—— C2) and paper mulching (—— C3).

FIGURE 2. Variation of soil moisture (cm^3 cm^{-3}) in irrigation depths and soil cover during the first cycle, 2019 (from **a** to **e**) and second cycle, 2020 (from **f** to **j**).

With the irrigation of 80% ID, soil moisture varied from 0.43 to 0.48 cm^3 cm^{-3} (first cycle and second cycle). Meanwhile, with irrigation of 100% ID, in the first cycle, the humidity was always at the field capacity (0.48 cm^3 cm^{-3}), but in the second cycle, there were alternations between 0.44 and 0.48 cm^3 cm^{-3}.

For the two cycles studied, the use of mulching on the soil resulted in smaller variations in soil moisture (Fig. 2). The plastic and paper mulching promoted greater water retention throughout the cycles, while the control treatment was the most unfavorable for the maintenance of water in the soil profile. In the control treatment, during all irrigation cycles, soil moisture varied between 0.41 and field capacity (FC) for the first cycle and from 0.36 cm^3 cm^{-3} to FC in the second cycle, and for treatments with mulching made of plastic and biodegradable paper, the moisture remained above 0.41 and 0.38 cm^3 cm^{-3} throughout the crop cycle, respectively for the years 2019 and 2020.

Water consumption in different soil covers

The actual water consumption in the cycles can be seen in table 3. In general, the average water demand of carrots at optimal irrigation level (100%) in the first cycle was 88.34 mm and 120.72 mm in the second cycle. When submitted to different soil covers, the actual water consumption varied. The treatment that consumed less water was mulching with biodegradable paper, on average in both cycles, with consumption of 80 mm in L1, 85 mm in L2, 88 mm in L3, 92 mm in L4, and 94 mm in L5.

TABLE 3. Total irrigation accumulated in the carrot crop (mm) in situations of irrigation depth and soil mulching for the first cycle (2019) and second cycle (2020).

Year	Soil Cover	Irrigation depths (%)				
		20 (L1)	40 (L2)	60 (L3)	80 (L4)	100 (L5)
2019	Control	69.45	74.71	82.48	89.16	94.79
	Plastic mulching	66.19	71.71	78.24	83.36	88.23
	Paper mulching	64.33	69.28	74.63	79.30	82.00
2020	Control	102.58	110.57	117.01	122.55	129.69
	Plastic mulching	99.48	107.78	113.62	119.26	125.61
	Paper mulching	95.65	100.72	102.64	105.09	106.87

Biometric variables

There was no significant interaction ($P > 0.05$) between irrigation and mulching factors for any of the variables studied. Consequently, the effects of the factors alone were evaluated.

Root length

Root length was influenced ($P < 0.01$) by soil cover in both cycles. In 2019 (first cycle) mulching with paper and the control treatment obtained the best results, respectively, reaching an average of 20.83 and 21.95 cm. In 2020 (second cycle), paper mulching was better than the other treatments (Table 4). Irrigation levels did not significantly influence the length of the carrot root.

TABLE 4. Average values of root length (R), root diameter (D), leaf height (H), normalized difference vegetation index (NDVI), yield (Y), and dry biomass (DB) of carrot (*Daucus carota* L.) as a function of soil cover in cycles 2019 and 2020.

Treatments	R (cm)		D (cm)		H (cm)		NDVI		Y (t ha^{-1})		DB (t ha^{-1})	
Year	2019	2020	2019	2020	2019	2020	2019	2020	2019	2019	2019	2020
Control	21.95a	17.21c	2.29c	3.37b	28.33b	44.19a	0.684a	0.783a	21.50b	24.76b	2.04a	2.23b
Plastic mulching	19.43b	18.78b	2.78b	3.65a	28.58b	47.33a	0.541b	0.708b	26.26ab	30.47a	2.45a	2.85ab
Paper mulching	20.83a	19.84a	3.20a	3.72a	31.38a	44.08a	0.626a	0.693b	28.35a	30.55a	2.42a	2.89a
Significant F test	**	**	**	**	**	^{ns}	**	**	**	**	^{ns}	*
CV (%)	8.74	7.81	10.6	9.8	8.97	10.72	15.95	8.39	26.06	22.66	28.26	31.4

Legend: significant F test at a probability level of 1% (**), 5% (*) and not significant at 5% probability (^{ns}); the means followed by the same letters of the line do not differ by the Tukey test ($P > 0.05$); coefficient of variation (CV).

Root diameter

The use of paper mulching provided higher mean values of root diameter (3.20 cm) in the first cycle with a significance of 1% error probability. Meanwhile in the second cycle, mulching with plastic and biodegradable paper was the best treatments and did not differ statistically from each other (Table 4).

Irrigation significantly affected ($P < 0.01$) the root diameter. With the regression equation of the first cycle, it was observed that irrigation in 100% compared to 20%, promoted an increase of 0.32 cm in diameter (Fig. 3a). In the second cycle, at each increase in the irrigation level, there was an increase of 0.11 cm in diameter, when compared to the previous irrigation level, reaching the maximum diameter in full irrigation (100%) with 3.8 cm.

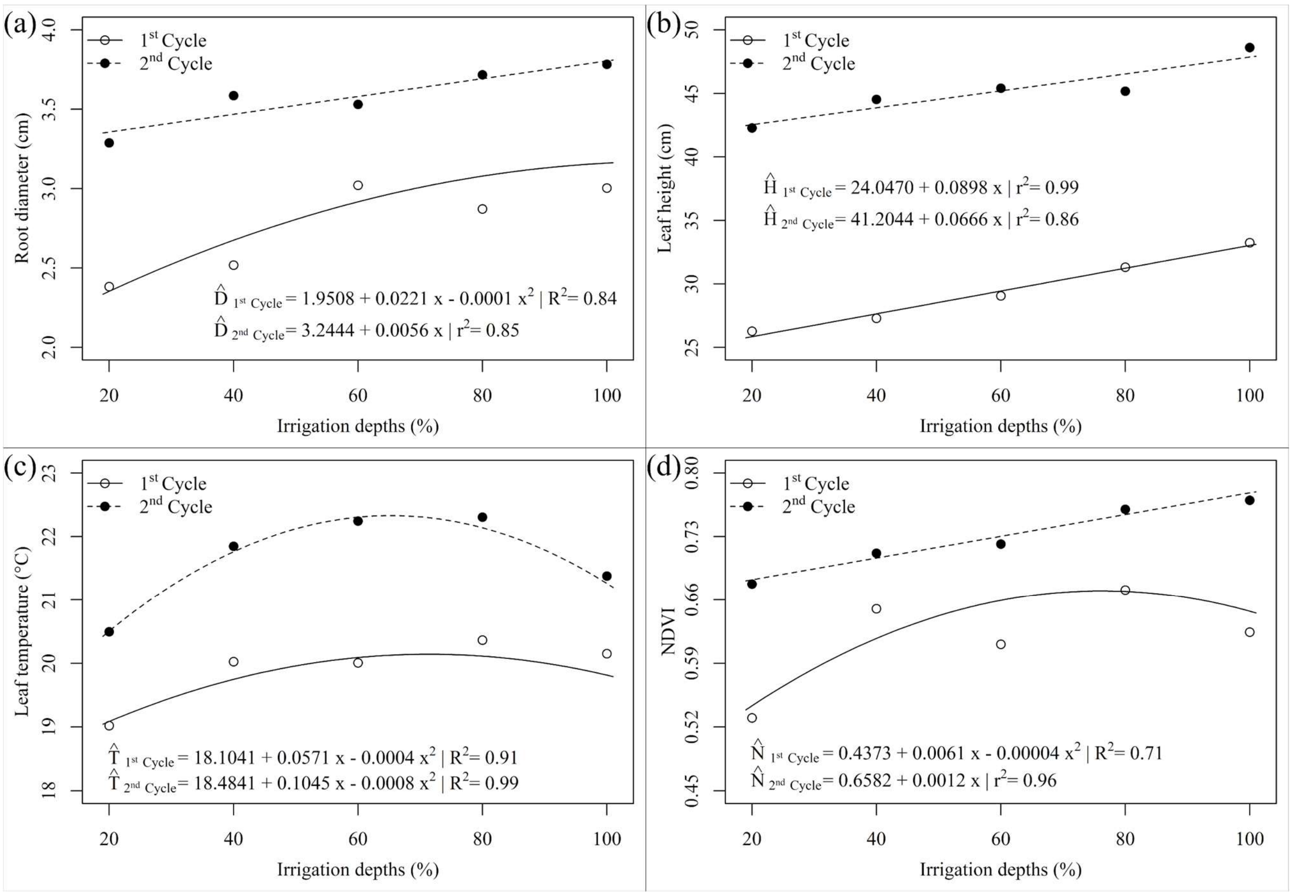


FIGURE. 3 Root diameter (a), leaf height (b), carrot leaf temperature (c), and normalized difference vegetation index (d) of carrot under different irrigation depths (%) for the years 2019 (first cycle) and 2020 (second cycle).

Height of leaves

Leaf height showed a significant response when submitted to different forms of soil mulching ($P < 0.01$) only in the first cycle. Paper mulching was better than the other treatments, reaching an average value of 31.38 cm (Table 4).

Irrigation influenced the height of carrot leaves ($P < 0.01$). In the first cycle, for each increase in irrigation level, there was an increase of 0.8 cm in the height of leaves, when compared to the level irrigation previously, reaching the maximum height (33 cm) in full irrigation (100%). In the second cycle, there was an increase of 0.33 cm in height, when comparing the irrigation level with the previous one, reaching the maximum height of 47 cm in full irrigation (100%) (Fig. 3b).

Leaf temperature

The leaf temperature of the carrot was not significantly affected by the soil cover. However, the irrigation level in the first and second cycles significantly affected the leaf temperature ($P < 0.05$ and $P < 0.01$, respectively). Using the adjustment equations (Fig. 3c), the maximum point in leaf temperature would be with the irrigation depth at 71.37% (first cycle) and 65.31% (second cycle) of the recommended, whose response in the plant indicates temperatures of 20.14 °C (2019) and 21.89 °C (2020).

Normalized difference vegetation index (NDVI)

The normalized difference vegetation index (NDVI) of the carrot was affected by soil cover treatments ($P < 0.01$). In the first cycle, the control treatment and paper mulching reached the best results with average values of 0.684 and 0.626, respectively. In the second cycle, the control treatment was better (0.783) than the other treatments (Table 4).

Irrigation levels influenced NDVI ($P<0.01$). In the first cycle, the maximum point described in the adjustment equation would be 76.25% of the ID, with the NDVI around 0.67. In the second cycle, for each increase in the irrigation level, there was an increase of 2.4% in the NDVI, when compared to the previous level, reaching a maximum NDVI of 0.77 with full irrigation (100%) (Fig. 3d).

Root yield

Soil cover affected carrot root yield (t ha^{-1}) in both cycles studied ($P < 0.01$). In the first cycle, root yield with the use of paper mulching reached about 28.35 t ha^{-1}, a result superior to the control (21.50 t ha^{-1}). In the second cycle, both mulching with paper or plastic can be used to increase crop yield when compared to the control treatment, with average productivity of 30 t ha^{-1} (Table 4).

As for the irrigation factor, a significant response was observed only in the second crop cycle ($P < 0.01$). In figure 4, productivity increases linearly with an increase in the irrigation level, reaching about 34.89 t ha^{-1} with irrigation at 100% of ID, which generates an increase of 53.23% relative to irrigation with 20% of ID (22.63 t ha^{-1}).

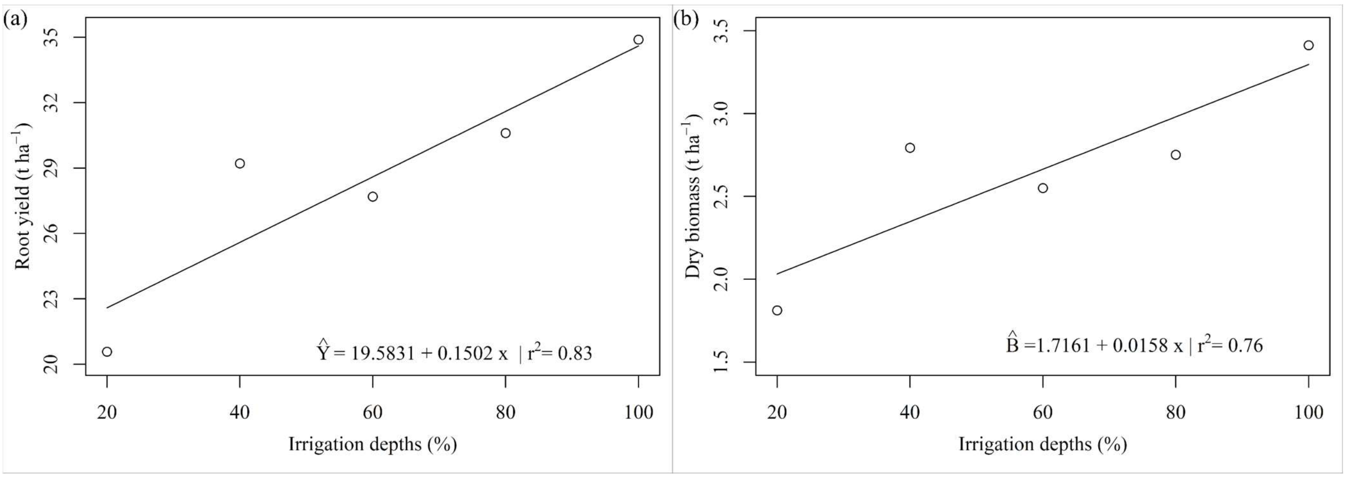


FIGURE 4. Root yield (a) and dry biomass (b) in t ha^{-1} of carrots under different irrigation depths (%) in 2020 (second cycle).

Dry biomass

In the second crop cycle (2020), there was a significant response for both the soil cover factor ($P < 0.05$) and irrigation depths ($P < 0.01$). Paper mulching expressed the highest dry mass accumulation (2.89 t ha^{-1}) compared to the control treatment (2.04 t ha^{-1}).

The dry root biomass showed a linear increase when submitted to different irrigation levels (Fig. 4b). For each increase in the irrigation level, there was an increase of 0.316 t ha^{-1} in dry biomass, when compared to the previous irrigation depth, reaching the maximum value of 3.29 t ha^{-1} with full irrigation (100%).

Discussion

Irrigation depths and the use of plastic and biodegradable paper mulching affected the temporal distribution of soil moisture. The irrigation deficit when associated with the use of mulching provided a decrease in oscillations in soil moisture and allowed the soil to remain closer to moisture at field capacity.

As in the present study, the use of mulching resulted in lower water applications compared to the control treatment. In addition, they will allow rainfall and water to remain available longer in the root zone. Thus, the use of mulching was an economical way to increase the time of availability of water for plants (Frezghi et al., 2021), in addition to reducing irrigation operations (He et al., 2018). These results corroborate the research of Chen et al. (2019) and Zheng et al. (2017).

Both cycles demonstrate different vegetative growth of carrots, with the best results being in the summer/autumn seasons (2020) compared to winter/spring (2019). As the carrot cultivar, 'Brasília' is a variety adapted to the summer, its best characteristics were best expressed at that time, which according to Resende et al. (2016) may indicate that the carrot outside this season is more susceptible to abiotic stress conditions.

Leaf height, for example, was significantly higher in the paper mulching treatment in 2019, possibly resulting from the better conditions of incident light on the leaf and soil (You et al., 2021) that the treatment promoted in a growing season that was unfavorable to cultivation, combined with an environment with low competition for water and nutrients. Meanwhile in 2020, the cultivar had its gene expression adequate for the climate, which inferred in a wide development of the area, regardless of the treatment tested.

In carrot primary growth, which occurs in the first 45 days after sowing, root length is highly influenced by the environment (Carvalho et al. 2015). In this period, paper mulching promoted the best condition for root elongation, due to the transmission and reflection of most of the solar radiation incident on the leaf and soil (You et al., 2021), while the treatment with plastic mulching had an adverse effect, caused by the absorption of much of the incident radiation from the crop and soil. (You et al., 2021).

Possibly as a result of this, when using plastic mulching, there was a significant increase in the heat flux in the soil, which increased soil temperature, a phenomenon already evidenced in the literature (Hayes et al., 2019; Marí et al., 2019; Zhang et al. 2019b). In the case of carrots, temperatures from 10 to 15 °C favor the elongation of the roots, while temperatures above 21 °C stimulate the formation of short roots (Embrapa, 2004). This explains why, in both cycles, the roots were shorter than in the other treatments.

Furthermore, the root length was not significantly affected by the irrigation depths, which differs from the results found by Reid & Gillespie (2017) and Carvalho et al. (2018). This difference was probably due to the contribution of rainfall in the experimental periods of this research (Fig. 1) differently from the studies cited, where there was no rainfall on the crops.

Secondary growth, which occurs from 45 days until close to harvest (±100 days for summer carrots), is marked by the expansion of the diameter (Carvalho et al. 2015). When applying deficit irrigation depths, smaller root diameters were obtained, as small changes in cell turgor during the cell growth process reflect a decline in cell expansion and growth (Jones, 2010; Taiz et al., 2017). Silva et al. (2011) and Reid & Gillespie (2017) also found that root diameters increased with increasing water stress.

The use of mulching during secondary growth had better results than the control treatment, since the soil cover resulted in smaller changes in soil moisture over time (Fig 2.) because the time of water availability allowed the best expansion of the upper diameter.

The higher average diameter values of paper mulching relative to plastic mulching are possibly due to the larger area of biomass accumulation at the reading site; however, measurements were not carried out in the average and smaller diameters, for better observation of the shape of the carrots.

The results of leaf temperature and leaf height together indicate that when there is water limitation, the vegetative vigor of carrots is lower. Leaf temperature determines the concentration or pressure of water vapor within the leaf and therefore determines the driving force of transpiration (Jones, 2010; Taiz et al., 2017) and the height of the leaves reflect in the greater photosynthetic apparatus of the plants. In this sense, leaf temperature can be converted into an indicator of stress by providing an indirect response of the plant to irrigation (Drechsler et al. 2019), while the height can be used as a non-destructive measurement for vegetative monitoring.

Another non-destructive measurement is the NDVI, which in this research also confirms that carrots subjected to lower irrigation depths reflect less of the infrared wavelengths. As the NDVI presents a positive correlation with the plant biomass (Rouse et al. 1973), it can be indirectly estimated that less vigorous plants will have a lower yield.

When using larger irrigation depths, the root yield (commercial product) presented higher yields, which is the same with the increase in photosynthetic equipment (plant height), water and nutrient accumulation (root diameter and dry biomass), thermal balance in leaves (leaf temperature) and which are reflected in plant vigor as observed in the NDVI graph. Similar results were found by Carvalho et al. (2018), where irrigation depths with 97.0% ETc replacement promoted the highest carrot yields.

The NDVI readings for the soil cover factor indicated that there was a difference in reflectance values between the plastic mulching and the other treatments, which may be related to the fact that the white polyethylene interfered with the reflection of the electromagnetic spectrum. The paper mulching, due to its brown coloration, suffered less interference at the time of reading. The lower reflectances in the first cycle may be related to the attack of insects and fungal disease, as the growing season is unfavorable to the cultivar, indicating a lower productive capacity of the plants.

Another way to evaluate the plant's productive capacity is through dry biomass accumulation, as it is highly related to photosynthetic production and plant nutrient accumulation (Jones, 2010; Taiz et al., 2017). Dry biomass was favored by the higher irrigations, corroborating the results obtained by Reid & Gillespie (2017) who found dry mass yields of carrots from 2.5 (2010) to 3.0 (2011) times higher for treatment with 100% of the required irrigation when compared to the dryland condition.

For the treatment of soil cover, the low yield of root and dry biomass in 2019 may be related to lower air temperatures during the growing time (Fig 1.), as well as by the recurrence of insects and fungal diseases. In 2020, with the best vegetative development of the cultivar, the mulching treatment of biodegradable paper was significantly equal to the cultivation with plastic mulching. Therefore, it can be a sustainable alternative, suitable for replacing plastic in agricultural cultivation (Marí et al., 2019; Henrique et al., 2021).

Zhang et al., 2019b when studying different soil covers, point out that paper mulching has a high potential for use in horticultural production, such as tomato, because, in general, the use of paper mulching improved the growth and roots of tomato plants, as well as in fruit yield.

Although in some variables studied the treatment with plastic mulching presented lower results, relative to yield, it had average values of 26 and 30 t ha^{-1}, possibly due to the shape acquired by carrots, with shorter lengths, but more cylindrical throughout their lengths, while the other treatments probably had a conical shape with greater elongation of the root, so with the use of plastic mulching, there was a high accumulation of biomass and water, confirmed by the average values found of dry biomass of the root. Chen et al. (2019) and Hou et al. (2019) found high yields of lettuce and sweet potatoes, respectively, when using plastic mulching.

CONCLUSIONS

The use of mulching promotes smaller variations in soil moisture and actual water consumption. Therefore, it implies lower water applications by irrigation in carrot cultivation compared to the control treatment.

The carrot cultivar 'Brasília' in both cycles, for the biometric variables studied, was sensitive to levels below 100% of the required daily irrigation depth. In this sense, for cultivation in the forest area of Minas Gerais, where carrot root yields above 34 t ha^{-1} are desired, the use of 100% of daily irrigation is indicated.

The technique of mulching with biodegradable paper in carrot cultivation is an option that equates the yield of mulching with plastic, surpassing it in characteristics such as root length, and in winter-autumn season in upper diameter of roots and height of leaves, and may be an ecologically suitable alternative to replace it. However, the association of irrigation management with the mulching technique should be validated in more carrot-producing regions as well as using other types of mulching in respect of the different regional realities observed in the Brazilian territory.

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