Agronomic characteristics of carrot cultivars under water stress

Características agronómicas de cultivares de zanahoria bajo estrés hídrico

Claudinei Martins Guimarães[1], Francisco Charles dos Santos Silva[2], Edcássio Dias Araújo[1], Aline Baldez Felismino Guimarães[1], Job Teixeira Oliveira[3*], Derly José Henriques da Silva[4], and Fernando França da Cunha[1]

ABSTRACT

The objective of the study was to evaluate the agronomic performance of carrot cultivars subjected to different levels of water supply. The experiment was conducted in a randomized block design, in a split-plot scheme with four replicates. Five irrigation depths were used in the plot, one to replace 100% of the crop's evapotranspiration (ETc), two in deficit (50 and 75% of ETc) and two in excess (125 and 150% of ETc). Four carrot cultivars were used in the subplots: Brasília, Alvorada, Esplanada, and Nantes. Two carrot cultivation cycles were carried out, the first lasting 121 d and the second lasting 103 d after sowing. The following variables were evaluated: total fresh mass of the plant, fresh carrot mass, carrot length, length of the aerial part, average carrot diameter, carrot volume, green shoulder, crop productivity, water productivity, and water potential of the plants. The Brasília carrot cultivar had better development and the Esplanada cultivar was less adapted to the studied environment. All carrot cultivars were affected by stress caused by excess and lack of water. Carrot irrigation must be carried out with a depth equal to 100% of the crop's evapotranspiration for the region and conditions similar to those of the present study.

Key words: *Daucus carota* L., protected cultivation, water deficit, water management.

RESUMEN

El objetivo del presente estudio fue evaluar el desempeño agronómico de cultivos de zanahoria sometidos a diferentes niveles de suministro de agua. El experimento se realizó en un diseño de bloques, en un esquema de parcelas divididas con cuatro repeticiones. En la parcela se utilizaron cinco profundidades de riego, una para reponer el 100% de la evapotranspiración (ETc) del cultivo, dos en déficit (50 y 75% de ETc) y dos en exceso (125 y 150% de ETc). En las subparcelas se utilizaron cuatro cultivares de zanahoria: Brasília, Alvorada, Esplanada y Nantes. Se realizaron dos ciclos de cultivo de zanahoria, el primero de 121 d y el segundo de 103 d después de la siembra. Se evaluaron las siguientes variables: masa fresca total de la planta, masa fresca de zanahoria, longitud de zanahoria, longitud de la parte aérea, diámetro promedio de zanahoria, volumen de zanahoria, hombro verde, rendimiento del cultivo, productividad del agua y potencial hídrico en la planta. El cultivo de zanahoria Brasilia mostró mejor desarrollo y el cultivo Esplanada estuvo menos adaptado al ambiente estudiado. Todos los cultivos de zanahoria se vieron afectados por el estrés causado por el exceso y la falta de agua. El riego de zanahoria se debe realizar con una profundidad igual al 100% de la evapotranspiración del cultivo para la región y condiciones similares a las del presente estudio.

Palabras clave: *Daucus carota* L., cultivo protegido, déficit hídrico, gestión del agua.

Introduction

Carrot (*Daucus carota* subsp. *sativus*), belonging to the Apiaceae family, is a root vegetable of great economic importance in Brazil and the world (Alves *et al*., 2020). Cultivated carrot is one of the most important vegetable plants in the world and favored by consumers for its typically sweet flavor (Schmid *et al*., 2021). Carrots are cultivated on a large scale in the Southeast, Northeast and South regions of Brazil, with an estimated planted area of 26000 ha and root production of 780000 t (Carvalho *et al*., 2017).

Scientific research into the carrot production process is necessary to meet this growing demand, reducing or eliminating deficiencies in the production sector. One potential solution to rectify these deficiencies involves selecting carrot varieties that are better suited to the climate and soil conditions of a particular region, facilitating enhanced crop productivity.

In conjunction with the selection of suitable genotypes tailored to the prevailing climate and soil conditions, the efficacy of carrot production hinges upon the implementation

Received for publication: September 22, 2023. Accepted for publication: December 9, 2023. Doi: 10.15446/agron.colomb.v41n3.112573

[1] Department of Agricultural Engineering, Federal University of Viçosa, Viçosa, MG (Brazil).
[2] Center for Advanced Studies of Balsas, State University of Maranhão, Balsas, MA (Brazil).
[3] Federal University of Mato Grosso do Sul, Chapadão do Sul Campus, Chapadão do Sul, MS (Brazil).
[4] Department of Agronomy, Federal University of Viçosa, Viçosa, MG (Brazil).
* Corresponding author: job.oliveira@ufms.br

of irrigation practices to adequately fulfill or supplement the crop's water requirements. According to Guimarães *et al*. (2019) and Nasir *et al*. (2021), carrot is a crop susceptible to water imbalances, making its rational management essential to maximize production.

Water deficit represents one of the primary climatic adversities faced by agricultural crops worldwide, and carrot (*Daucus carota* subsp. *sativus*) cultivation is no exception (Cunha *et al*., 2019; Mustafa *et al*., 2022). Under conditions of water deficit, carrots manifest an array of physiological and biochemical reactions that adversely affect their growth and, consequently, yield potential. Water scarcity impairs nutrient uptake, reduces the rate of photosynthesis, disrupts nutrient transport, and hampers the growth of roots, which are the commercially valuable part of the plant (Zhao *et al*., 2022; Rosińska *et al*., 2023). Therefore, evaluating and understanding the effects of water deficit on carrot cultivation is of paramount importance. Research in this field is essential for developing proper management strategies, such as efficient irrigation and the development of drought-resistant varieties, to ensure food security and the sustainability of carrot production in an increasingly challenging climate change scenario (Abbas *et al*., 2023; Kwiatkowski *et al*., 2023). Excess water also causes problems for agricultural crops due to the reduction of free porosity and leaching of nutrients (Li *et al*., 2018; Massa *et al*., 2020; Santos & Silva, 2020). Therefore, research is important to verify the behavior of carrot crops in different water availability. This information is important for production estimates, economic analysis, and decision-making in commercial crops. In this way, the producer will be able to better plan for different water availability scenarios.

The use of irrigation enables successive crops throughout the year (Drysdale & Hendricks, 2018; Cunha *et al*., 2019). Irrigation is necessary in a protected environment to meet the plant's water needs. The use of protected environments has become more frequent in recent years, as they protect the crop from climatic adversities, pests and diseases, providing an increase in productivity and product quality (Gómez *et al*., 2019; Nikolaou *et al*., 2019; Martínez-Gómez *et al*., 2021; Filgueiras *et al*., 2022).

Given the above, we tested the hypothesis that water stress, whether due to excess or deficit, affects different carrot cultivars. Thus, the objective of this study was to evaluate the agronomic performance of carrot cultivars subjected to different levels of water supply.

Materials and methods

Characterization of the area and experimental test

The research was conducted in a greenhouse at the Federal University of Viçosa (UFV, Brazil), in Viçosa-MG, at coordinates 20°45'14'' S, 42°52'55'' W, altitude of 648 m a.s.l. The climate, according to the Köppen classification, was type Cwb (Alvares *et al*., 2013). The average annual temperature was 19.4°C and the annual rainfall was approximately 1,200 mm.

A greenhouse with a total area of 240 m^2 and dimensions of 8 m wide and 30 m long was used. The sides were covered with polyethylene yarn fabric, with the following characteristics: 100% polyethylene, 25 mesh - 1.0 x 1.0 mm opening, with 10 yarns per cm of fabric - and 25% shading. The ceiling was covered with blue plastic film, with the following characteristics: AV Blue, 120 µm, 78% and 67% light transmission and diffusion, respectively. The greenhouse was not controlled for air temperature, relative humidity or CO_2 concentration. Two carrot cultivation cycles were carried out. Cycle 1 lasted 121 d (18/01/2017 to 18/05/2017) and cycle 2 lasted 103 d (04/08/2017 to 14/11/2017) after sowing. In both carrot growth cycles, there was an accumulation of 1,500 growing degree days. To calculate the accumulation of growing degree days, air temperatures of 10ºC were used as the lower base and 30ºC as the upper base (Embrapa, 2004).

The experimental design was in randomized blocks (DBC), with four replicates, in a split-plot scheme, with five irrigation depths in the plots and four carrot cultivars in the subplots. The irrigation depths were used to replace 50, 75, 100, 125, and 150% of the crop's evapotranspiration (ETc). The carrot cultivars were: Brasília, Embrapa (2004), summer cultivar; Alvorada, Embrapa (2003), summer cultivar; Esplanada, Embrapa (2005), spring-summer cultivar; and Nantes, Embrapa (2004), autumn-winter cultivar. The carrot varieties selected for the present study were those with the greatest potential and/or most cultivated in the state of Minas Gerais, which is the largest carrot producer in Brazil (Alves *et al*., 2020). Each sampling unit (subplot) had an area of 1 m^2 (1 m long and 1 m wide), consisting of four rows of plants (0.25 m between rows and 0.06 m between plants), resulting in a planting density of 66 units per m^2. For the evaluations, four plants were sampled in the center of the center lines in each subplot.

Data from 80 observations (5 irrigation depths x 4 replicates x 4 carrot cultivars) were used for each characteristic analyzed for each cultivar and for each cycle.

Installation and conduction of research

A eutrophic Red-Yellow Oxisol was used, with the characteristics presented in Table 1. Soil sampling was carried out inside the protected environments to carry out physicochemical analysis (Tab. 1).

The soil preparation was done through plowing and harrowing, using a ridger. Liming and chemical fertilization were carried out based on the soil chemical analysis results and recommendations from Ribeiro *et al.* (1999). Before sowing, 5 t ha^{-1} of cattle manure were incorporated into the soil. For mineral fertilization, 50 kg ha^{-1} of P_2O_5, 75 kg ha^{-1} of K_2O, and 40 kg ha^{-1} of N were applied using simple superphosphate, potassium chloride, and urea, respectively. Fifteen kg ha^{-1} of borax and 15 kg ha^{-1} of zinc sulfate were also applied.

Carrots were sown directly in the beds (in small furrows spaced 0.25 m between rows) and subsequently, thinning was carried out (0.06 m spacing between plants) 28 d after sowing, similar to Silva *et al.* (2019). Weekly, manual weeding was carried out until the soil was naturally shaded by the aerial part of the plants. Incidences of pests and diseases capable of causing significant damage to carrot quality and productivity were not observed.

The drip irrigation system was used, with lateral lines made up of drip tapes (Amanco brand) 16 mm in diameter and 15 thousandths of an inch (2.54 cm) thick. The spacing between the drip tapes was 0.50 m, which made it possible to irrigate two rows of plants. The emitters (drippers), spaced 0.20 m apart, operated with a working pressure of 98 kPa (~10 mwc), applying an average flow of 1.8 L h^{-1}. The water for irrigation was stored in a 15 m^3 reservoir and had a pH of 6.7 and electrical conductivity of 57 μS cm^{-1}. The irrigation water also had a total hardness of 16 mg L^{-1} and total dissolved solids of 15 mg L^{-1}.

Climate data

Meteorological data were obtained using the automatic meteorological station E 4000 (IRRIPLUS), installed centrally inside the greenhouse. Data on solar radiation (Rs), mean air temperature (T_a), and relative humidity (RH) were measured at 5-min intervals. The collected meteorological data were converted to a daily scale, and, subsequently, ETo values were calculated using the Penman-Monteith method (Allen *et al.*, 1998).

Due to the lack of rainfall inside the greenhouse, there was no need to collect this variable. This circumstance also influenced the application of treatments, as rain could have disrupted the imposition of treatments with different irrigation levels.

Irrigation management

The irrigation system was evaluated using the methodology proposed by Bernardo *et al.* (2019), which consists of collecting the dripper flow at eight points along the lateral line and at four lateral lines, along the derivation line. The distribution efficiency was 92.4%, according to the distribution uniformity coefficient, calculated using Equation 1:

$$\mathrm{DUC} = \frac{\mathrm{Flo25\%}}{\mathrm{FloM}} 100 \qquad (1)$$

where: DUC – distribution uniformity coefficient, %; Flo25% – average of the lowest quartile of flows, L h^{-1}; and FloM – average flow rate, L h^{-1}.

The actual irrigation required to treat 100% of ETc was estimated as a function of climate and soil characteristics parameters, using Equation 2, adapted from the equation proposed by Bernardo *et al.* (2019):

TABLE 1. Physicochemical characteristics of soil at 0-0.20 m soil depths at the experiment site.

FC*	PWP*	BD	PD	Sp	Clay	Silt	Sand	Textural classification
kg kg^{-1}		kg m^{-3}	kg m^{-3}	%	%			
0.291	0.177	1,210	2,641	54.2	39	11	50	Sand clay

pH	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB	t	T	V	m	Prem	Ec
H_2O	mg dm^{-3}		cmol$_c$ dm^{-3}							%		mg L^{-1}	μS cm^{-1}
6.1	328.4	196.0	5.4	1.2	0.0	2.6	7.2	7.2	9.8	73.3	0.0	51.5	145

FC*: field capacity (matric potential of -33 kPa); PWP*: permanent wilting point (matric potential of -1,500 kPa); *obtained from the soil water retention curve using the Richards extractor; BD: bulk density; PD: particle density; Sp: soil porosity; SB: sum of bases; t: effective cation-exchange capacity; T: cation-exchange capacity; V: base saturation; m: aluminum saturation; Prem: remaining phosphorus according to the methodology by Teixeira *et al.* (2017); Ec: electric conductivity at 25°C. Available P and K extracted with Mehlich I; exchangeable Ca, Mg and Al extracted with 1 mol L^{-1} KCl ; potential acidity at pH 7.0 extracted with 0.5 mol L^{-1} calcium acetate.

$$AIR_{LOC} = \sum_{day\ 1}^{i} ETo\ K_C\ K_S\ K_L - C \quad (2)$$

where: AIR_{LOC} – actual irrigation required in localized systems, mm; ETo – reference evapotranspiration, mm d^{-1}; K_C – crop coefficient, dimensionless; K_S – soil moisture coefficient, dimensionless; K_L – location coefficient, dimensionless; and C – constant referring to the elevation of the water table, mm.

The model used to estimate ETo was the Penman-Monteith FAO-56 (Allen *et al*., 1998) according to Equation 3. Wind speed was considered equal to 0.2 m s^{-1}, as recommended for indoor protected environments (Guimarães *et al*., 2019; Correia *et al*., 2020).

$$ETo = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{37}{T_a + 273} U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,U_2)} \quad (3)$$

where: ETo – reference evapotranspiration, mm h^{-1}; R_n – net radiation on the surface, MJ m^{-2} h^{-1}; G – soil heat flux density, MJ m^{-2} h^{-1}; T_a – average air temperature, °C; U_2 – wind speed at 2 m height, m s^{-1}; e_s – saturation vapor pressure, kPa; e_a – partial vapor pressure, kPa; Δ – slope of the saturation vapor pressure curve, kPa °C^{-1}; γ – psychrometric coefficient, kPa °C^{-1}.

Cultivation coefficient (K_C) values were used in accordance with the literature (Cunha *et al*., 2016). The K_C used was determined according to the stage of crop development: phase I – initial growth; phase II - vegetative growth; phase III - root thickening; phase IV - pre-harvest. For phases I, II, III and IV, a K_c of 0.7, 0.9, 1.0, and 1.1 was adopted, respectively.

Soil moisture (K_S) and location (K_L) coefficients were calculated according to Bernardo *et al.* (2019):

$$K_S = \frac{Ln\,(CWD + 1)}{Ln\,(TWC + 1)} \quad (4)$$

$$K_L = \frac{P}{100} + 0.15\left(1 - \frac{P}{100}\right) \quad (5)$$

where: K_S – soil water depletion coefficient, dimensionless; CWD – current water depth, mm; TWC – total water capacity, mm; K_L – location coefficient, dimensionless; P – highest value among percentage of wet or shaded area, %.

The AIR_{LOC} value was corrected depending on the irrigation efficiency, defining the total irrigation required for localized systems (TIR_{LOC}).

$$TIR_{LOC} = \frac{AIR_{LOC}}{Ie} \quad (6)$$

where: TIR_{LOC} – total irrigation required in localized systems, mm; AIR_{LOC} – actual irrigation required in localized systems, mm; Ie – irrigation efficiency, decimal.

Figure 1 shows the water balance for the treatment that received an irrigation sheet to replace 100% of ETc. This figure shows the current soil moisture and the irrigation levels applied in the two carrot cultivation cycles. In cycle 1, soil moisture was below the critical point only twice (02/1/2017 and 05/08/2017). In cycle 2, this situation did not occur at any time. It can also be seen in Figure 1 that irrigations were more frequent at the beginning of the cultivation cycles since the root system was shallow and there was less water availability in the soil.

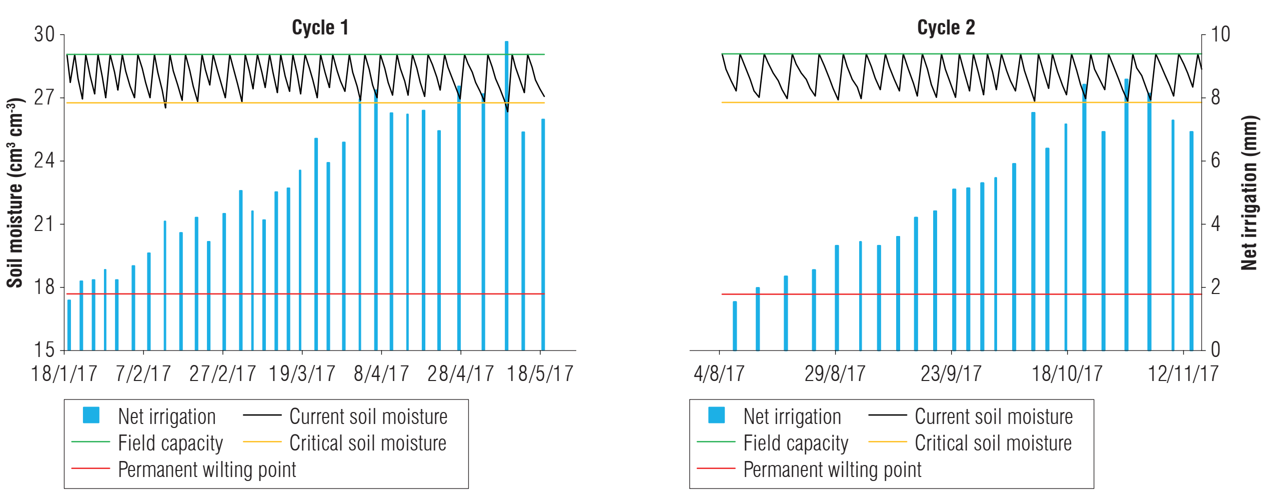


FIGURE 1. Water balance to meet 100% of crop evapotranspiration in two carrot cultivation cycles.

The application efficiency was 100% and the average distribution efficiency 92.4%. Thus, the irrigation efficiency was 92.4% for the two cultivation cycles.

For 5 d before the start of irrigation management via climate, the water content in the soil was monitored at a depth of 0-0.20 m, using tensiometers based on the soil water retention curve $\theta_{Azul} = 0.1813 + (0.3443 - 0.1813) / (1 + (0.01 |\Psi_m|)^2)^{0.49}$ and by the direct greenhouse method, in order to guarantee soil moisture at field capacity conditions. The differentiation of irrigation depths began 30 d after sowing.

To maintain pressure uniformity in the system during the irrigation time, two lateral lines were always kept open simultaneously: irrigation time = 20 min, L1=10 min (50% of ETc), L2=15 min (75% of ETc), L3=20 min (100% of ETc), L4=25 min (125% of ETc), and L5=30 min (150% of ETc).

The carrot crop was grown in two cycles lasting 121 and 103 d. The experiments were conducted in a randomized block design, in a split-plot scheme with four replicates. Four carrot cultivars were added to the subplots: Brasília, Alvorada, Esplanada, and Nantes.

Variables analyzed

Carrot harvests occurred when 1,500 growing degree-days were accumulated for all varieties. The variables analyzed in carrot cultivation are presented in Table 2.

Statistical analysis

The data were subjected to analysis of variance at 5% and 1% probability, using the F test. When significant at 5%, the effects of irrigations were subjected to regression analysis and the effects of cultivars were compared using the Tukey´s test 5% probability.

For regression analysis, the linear, quadratic, cubic, square root, potential, exponential, hyperbolic, logarithmic, cubic-root, log-log, Ln-Ln and Exp (x) models were tested. To choose the best model, the following were considered: the significance of the F test for the regression equation at 5% probability, the coefficient of determination (R^2), and the representation of biological behavior by the equations.

Parameter data were subjected to principal component analysis (PCA). The GENES and SISVAR software were used for statistical analyses.

TABLE 2. The variables analyzed in carrot cultivation.

Description	Parameter	Unit	Method
Carrot length	CL	cm	measured with a ruler
Plant length	AL	cm	aboveground length measured with a ruler
Average carrot diameter	ACD	mm	average of three measurements (shoulder, middle and tip) using a caliper
Carrot volume	CV	cm^3	by displacement of water volume inside a millimeter beaker
Green shoulder	GS	cm	thickness of the greenish color in the “shoulder” of the carrot, measured with a caliper
Damaged carrots	DC	un 10^{-1}	number of unmarketable carrots due to damage, out of 10 carrots randomly collected in the useful plot
Fresh carrot mass	FCM	g	wet mass of whole carrots only
Dry carrot mass	DCM	g	whole carrot mass, dried in a forced ventilation oven at 70°C, until reaching a constant mass
Fresh foliage mass	FAM	g	wet mass of the aerial part of the plant
Dry foliage mass	DAM	g	mass of the aerial part dried in a forced ventilation oven at 70°C, until reaching a constant mass
Mass of 10 carrots	10CM	g	fresh mass of 10 carrots collected randomly from the useful plot
Crop yield	CY	m^{-2}	estimate of the ratio between the production of 10 carrots from the useful plot and the area occupied by them, extrapolating to an area of 1 ha, considering the use of access corridors of 0.40 m wide and maximum bed length of 50 m and using roots free from defects, such as cracks, bifurcations, nematodes and mechanical damage, with length and diameter greater than 5.0 and 1.0 cm, respectively, according to Soares *et al.* (2010)
Water productivity	WP	m^{-3}	obtained by the relationship between the mass of fresh matter of the plant (kg ha^{-1}) and the amount of water applied (mm) for each treatment
Plant water potential	Ψp	kPa	estimated using the Scholander chamber methodology (Scholander *et al.*, 1964). Two measurements were taken per cycle (one at 55 d after sowing and another 2 d before harvest), following the recommendation of the methodology, with measurements obtained between 3:00 am and 6:00 am (before sunrise – predown), when the water potential in the plant is maximum. The analysis was carried out on two leaves per plant, obtained from two different plants in the subplots

Results and discussion

Climate data

The average solar radiation (Rs) was 7.1 MJ m^{-2} d^{-1} in cycle 1 (ranging from 1.6 to 11.0 MJ m^{-2} d^{-1}) and 6.2 MJ m^{-2} d^{-1} in cycle 2 (ranging from 1.8 to 9.1 MJ m^{-2} d^{-1}). The daily average Rs decreased throughout cycle 1 and this behavior influenced the decrease in Tmean and ETo (Fig. 2). The average daily air temperature ranged from 16.5 to 26.4°C in cycle 1 (average of 22.4°C) and from 15.4 to 35.3°C in cycle 2 (average of 21.2°C). The daily average relative air humidity (RH) ranged from 61.1 to 87.6% (average of 77.7%) and from 58.6 to 93.5% (average of 77.4%) in cycles 1 and 2, respectively.

ETo presented daily average values equal to 1.8 mm d^{-1} (oscillation from 1.0 to 2.6 mm d^{-1}) in cycle 1 and equal to 1.7 mm d^{-1} (from 1.0 to 2.3 mm d^{-1}) in cycle 2. The ETo occurring throughout each carrot cultivation cycle was used to determine the actual irrigation required (AIR) and total irrigation required (TIR) for an irrigation depth of 100% of the ETc applied in the treatments.

Water consumption

Due to the absence of rainfall within the protected environment, a high frequency of irrigation (2-d irrigation shift) was required. The soil was maintained with moisture close to field capacity and with little water requirement to equal the total storage capacity at the time of each irrigation (Tab. 3).

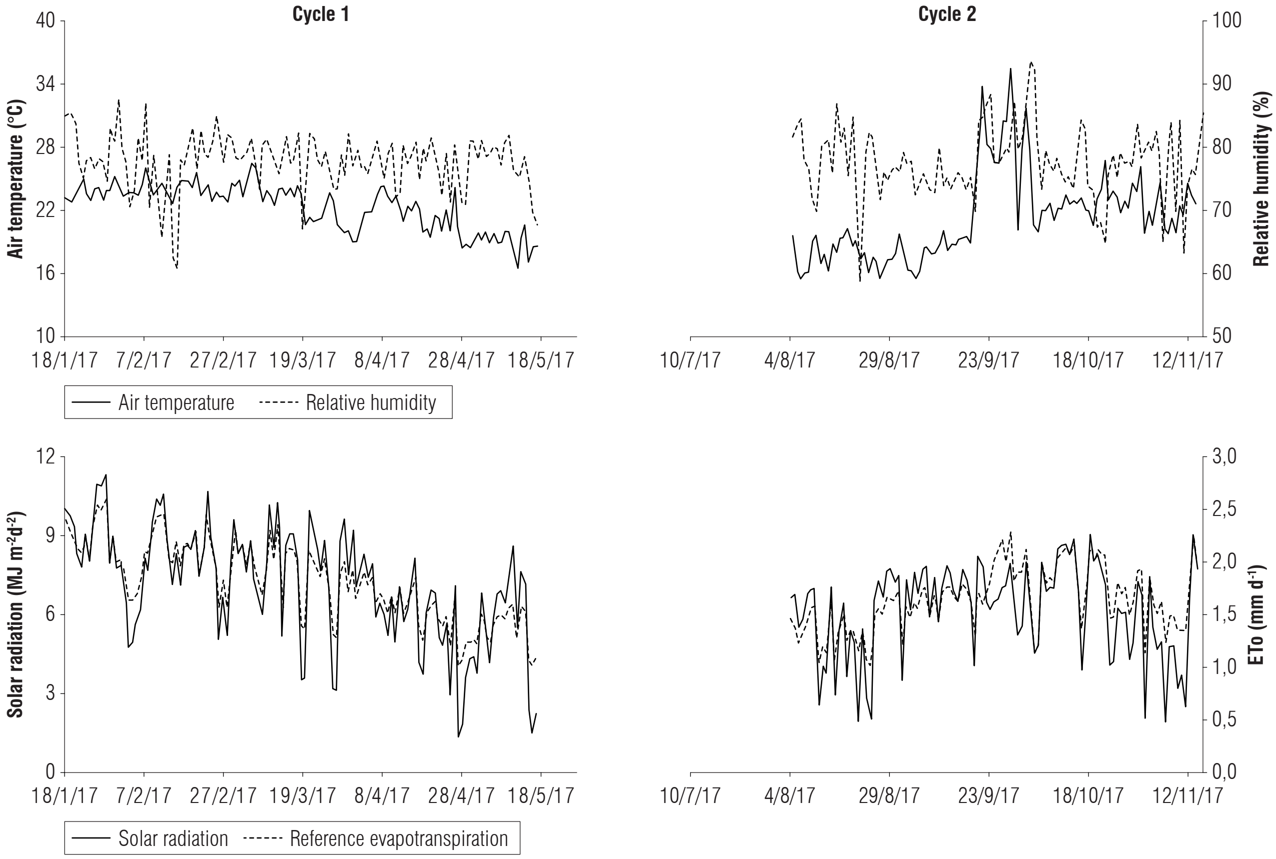


FIGURE 2. Daily variation in air temperature (°C), relative air humidity (%), solar radiation (MJ m^{-2} d^{-1}) and reference evapotranspiration (Eto mm d^{-1}) for the two carrot cultivation cycles in 2017.

TABLE 3. Actual and total required irrigation applied in each carrot treatment and growing season. Viçosa, MG (Brazil), 2017.

Cycle	Parameter	Irrigation depths (% of ETc)				
		50	75	100	125	150
1	Actual irrigation required (mm)	84.6	126.9	169.2	211.5	253.8
	Total irrigation required (mm)	91.6	137.3	183.1	228.9	274.7
2	Actual irrigation required (mm)	61.7	92.5	123.3	154.1	185.0
	Total irrigation required (mm)	66.7	100.1	133.4	166.8	200.2

Carrot cycle 1 showed higher water consumption due to meteorological elements that caused a higher average ETo in this cycle compared to the cultivation cycle 2. The drip irrigation system showed an efficiency of 92.4%.

Agronomic characteristics

There was no interaction between irrigation depths and carrot cultivars for any of the characteristics evaluated (Tabs. 4-5). This demonstrates that water supply affects carrots regardless of the variety being cultivated. Stress due to excess or deficit of water will have the same effect on carrot varieties, which confirms the hypothesis of the present study. On the other hand, significance was observed, using the F test, for both the irrigation depth and carrot cultivars, independently. When there was no interaction between the factors (cultivar and environment) or significance in any of the factors evaluated.

Although crop yield did not vary significantly (P>0.05) between the cultivars, higher dry carrot mass and mass of 10 carrots values were observed for the Brasília cultivar, which tends to adapt better to the conditions of the protected environment studied. As the number of days until harvest

TABLE 4. Mean squares, of plant water potential (Ψp), aboveground length (AL), fresh aboveground mass (FAM), dry aboveground mass (DAM), carrot length (CL), average carrot diameter (ACD), carrot volume (CV), green shoulder (GS), damaged carrots (DC), fresh carrot mass (FCM), dry carrot mass (DCM), mass of 10 carrots (10CM), crop yield (CY) and water productivity (WP) as a function of different cultivars (Cult) and irrigation depths (ID) in two cultivation cycles.

Parameter	Cycle	Mean square		
		ID	Cult	ID x Cult
Ψp	1	2.0E+4^{ns}	4.9E+5**	6.2E+4^{ns}
(kPa)	2	8.2E+4^{ns}	1.2E+6**	4.1E+4^{ns}
AL	1	1.5E+2**	1.3E+2**	7.4E+1^{ns}
(cm)	2	9.0E+1**	2.1E+1^{ns}	9.9E+0^{ns}
FAM	1	3.2E+3**	2.5E+3^{ns}	1.8E+3^{ns}
(g)	2	7.0E+2**	9.4E+1^{ns}	9.4E+1^{ns}
DAM	1	6.6E+1*	6.9E+1^{ns}	3.0E+1^{ns}
(g)	2	6.3E+0^{ns}	3.1E-1^{ns}	1.9E+0^{ns}
CL	1	1.2E+1^{ns}	8.3E+1**	1.7E+1^{ns}
(cm)	2	9.5E+0^{ns}	4.7E+1**	3.9E+0^{ns}
ACD	1	7.6E+1^{ns}	1.1E+2**	2.8E+1^{ns}
(mm)	2	1.8E+1^{ns}	2.0E+1*	3.8E+0^{ns}
CV	1	8.8E+3*	5.9E+3^{ns}	4.7E+3^{ns}
(ml)	2	1.8E+3*	1.3E+3^{ns}	3.7E+2^{ns}
GS	1	2.4E+1^{ns}	7.0E+1^{ns}	2.5E+1^{ns}
(cm)	2	1.4E+1^{ns}	3.7E+0^{ns}	4.9E+0^{ns}
DC	1	2.3E+0^{ns}	3.5E+0^{ns}	1.6E+1^{ns}
(un/10)	2	7.7E-1^{ns}	3.8E-1^{ns}	2.0E-1^{ns}
FCM	1	6.9E+3^{ns}	8.9E+3^{ns}	4.5E+3^{ns}
(g)	2	2.4E+3*	1.6E+3^{ns}	4.0E+2^{ns}
DCM	1	7.1E+1^{ns}	3.0E+2*	1.0E+2^{ns}
(g)	2	1.2E+1^{ns}	7.0E+1*	1.6E+1^{ns}
10CM	1	5.0E+5*	3.7E+5*	2.0E+5^{ns}
(g)	2	1.9E+4^{ns}	4.9E+4**	6.1E+3^{ns}
CY	1	2.3E+8^{ns}	1.5E+9^{ns}	7.5E+8^{ns}
(kg m^{-2})	2	4.0E+8*	2.7E+8^{ns}	6.6E+5^{ns}
WP	1	1.6E+4**	1.5E+3^{ns}	6.6E+2^{ns}
(kg m^{-3})	2	3.2E+3**	2.4E+2^{ns}	4.8E+1^{ns}

ID x Cult: interaction between ID and Cult; ETc: crop evapotranspiration; * and **: significance at 5% and 1% probability, respectively.

TABLE 5. Significance of the F test and mean values of plant water potential (Ψp), aboveground length (AL), fresh aboveground mass (FAM), dry aboveground mass (DAM), carrot length (CL), average carrot diameter (ACD), carrot volume (CV), green shoulder (GS), damaged carrots (DC), fresh carrot mass (FCM), dry carrot mass (DCM), mass of 10 carrots (10CM), crop yield (CY) and water productivity (WP) as a function of different cultivars (Cult) and irrigation depths (ID) in two carrot cultivation cycles.

Parameter	Carrot cultivars			
	Brasília	Alvorada	Esplanada	Nantes
Ψp	730.9 b	755.0 b	730.8 b	1051.5 a
(kPa)	1261.7 a	1275.5 a	973.9 b	779.1 b
AL			$\bar{y}$ = 66.6	
(cm)			$\bar{y}$ = 43.4	
FAM			$\bar{y}$ = 83.4	
(g)			$\bar{y}$ = 26.1	
DAM			$\bar{y}$ = 13.1	
(g)			$\bar{y}$ = 11.2	
CL	21.3 ab	18.6 b	21.2 ab	23.6 a
(cm)	15 a	13.2 b	16.5 a	16.5 a
ACD	35.1 ab	36.8 a	31.8 b	32.5 b
(mm)	25.8 ab	25.4 ab	23.8 b	26.1 a
CV			$\bar{y}$ = 230.9	
(ml)			$\bar{y}$ = 80.7	
GS			$\bar{y}$ = 12.5	
(cm)			$\bar{y}$ = 7.8	
DC			$\bar{y}$ = 1.4	
(un/10)			$\bar{y}$ = 0.83	
FCM			$\bar{y}$ = 224.9	
(g)			$\bar{y}$ = 89.5	
DCM	40.5 a	34.2 ab	31.5 b	37.1 ab
(g)	15.3 a	12.6 ab	11.2 b	14.7 ab
10CM	1805.0 a	1511.4 b	1559.4 ab	1532.9 ab
(g)	708.7 a	637.9 ab	591.2 b	626.6 b
CY			$\bar{y}$ = 9.2	
(kg m^{-2})			$\bar{y}$ = 3.6	
WP			$\bar{y}$ = 85.2	
(kg m^{-3})			$\bar{y}$ = 39.3	

Means followed by the same letter in the line do not differ significantly according to the Tukey test (P<0.05).

was the same for all cultivars analyzed, the precocity of the Brasília cultivar probably favored it, allowing more time for root development in relation to the other cultivars. Due to its ability to adapt and prosper in the environment of the present study, the Brasília cultivar will present greater economic viability, improving the farmer's income. Larger carrots can offer advantages such as industrial processing efficiency, consumer appeal and practicality in certain culinary preparations.

In contrast, the Esplanada cultivar proved to be less adapted to the environment studied. Their responses to greenhouse conditions were less favorable, resulting in lower performance in several agronomic characteristics. The inferiority of Esplanada in relation to Brasilia may have been caused by genetic differences. This indicates that although the Esplanada cultivar may be suitable for other growing conditions or environments, its performance in this specific environment was limited compared to the Brasília cultivar.

The Alvorada and Nantes cultivars were intermediate between the two cultivars. Although the Nantes cultivar is recommended for regions or seasons with milder temperatures (cold climate), in general, it presented intermediate development. The coverage with blue plastic film used in the study environment reduced the direct incidence of light on the plants. In the experiment, the irrigation levels were controlled and lower than the rainy periods that occur in the Brazilian summer. Furthermore, the experiment was carried out in a region far from carrot production centers, which contributes to the low inoculum pressure of foliar diseases that attack this crop in the summer. The use of plastic film compared to the external environment provided increases of 5.0% and 7.1% in air temperature for cultivation cycles 1 and 2, respectively.

The crop yield values in both cycles can be considered high, indicating that the experimental conditions provided the cultivars with adequate expression of their productive potential. It is worth highlighting that experiment averages were almost always higher than national production averages. The yields were higher than the world averages of 2.2 kg m^{-2} and 3.0 kg m^{-2} and higher than the national averages of 2.9 kg m^{-2} and 3.1 kg m^{-2} reported by Resende and Braga (2014) and by Carvalho *et al.* (2017), respectively.

The discrepant values of the crop yield between the two carrot cultivation cycles (Tab. 3), possibly, occurred due to the variation between the cycles of potential soil salinity caused by high salt contents accumulated in the soil used in the present research. The maximum and minimum temperatures during the period may also have contributed. Resende and Cordeiro (2007) found a variation in carrot productivity from 3.7 to 8.1 kg m^{-2} (also higher than the world and national averages mentioned) depending on the quality of the irrigation water applied. The highest value of electrical conductivity (8.0 dS m^{-1}) promoted the lowest productivity (3.3 kg m^{-2}) and the lowest electrical conductivity (normal water at 0.1 dS m^{-1}) increased carrot productivity (8.1 kg m^{-2}).

The reduction in solar radiation (Fig. 2) within the protected environment, for cycle 2 compared to cycle 1, possibly, reduced the photosynthetic rate of the carrot crop in cycle 2, contributing to the difference in crop yield between cycles. However, there were no measures implemented in cycle 2 to compensate for this reduction in solar radiation, as no variations in performance were anticipated.

Luz *et al.* (2009) found carrot yield values of 3.8, 3.6, and 3.1 kg m^{-2} for the cultivars Brasília, Alvorada and Nantes, respectively, grown in open field. Resende and Braga (2014) found higher yield values for carrot crops: Brasília (9.6 kg m^{-2}), Alvorada (8.2 kg m^{-2}), Esplanada (6.5 kg m^{-2}), and Nantes (7.0 kg m^{-2}). Such crop yield values were close to those found in cycle 1 of the present study. This result reinforces that the study was well conducted in both cycles. It also reinforces that the results found were sufficient to elaborate the conclusions of the study.

The behavior of the agronomic characteristics of the studied carrot cultivars, depending on the different irrigation depths, is shown in Figure 3. The aboveground length (AL) and dry aboveground mass (DAM) of cycle 1 showed quadratic behavior depending on the irrigation depths. According to the regression equations, the irrigation depths that maximized AL and DAM were 143% of ETc and 128% of ETc, with values of 68.9 cm and 14.3 g, respectively. Water productivity (WP) in cultivation cycle 1 also showed quadratic behavior, with the irrigation depth of 145% of ETc minimizing this characteristic, with a value of 57.9 kg m^{-3}. The other agronomic characteristics suffered a linear effect, in which WP decreased as water supply increased and the others showed a positive effect.

The highest values of the agronomic characteristics that confer better plant development were obtained by applying the highest irrigation depth studied (150% of ETc), which is higher than 100% of the ETc replacement. This possibly occurred due to the overall efficiency of the system.

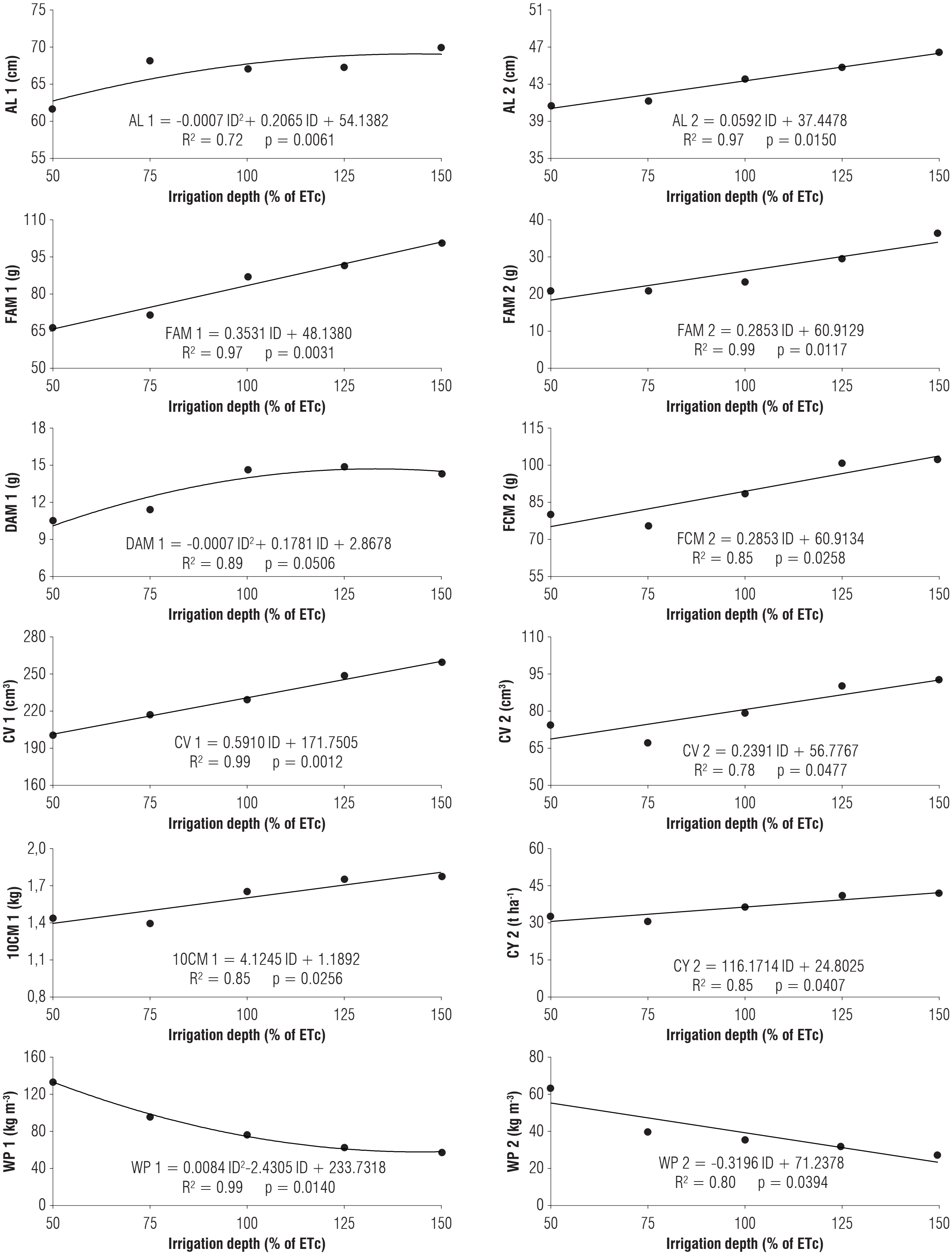


FIGURE 3. Average values of aboveground length (AL), fresh aboveground mass (FAM), dry aboveground mass (DAM), fresh carrot mass (FCM), carrot volume (CV), mass of 10 carrots (10CM), crop yield (CY), and water productivity (WP) for cultivation cycles 1 and 2 as a function of irrigation depths (ID).

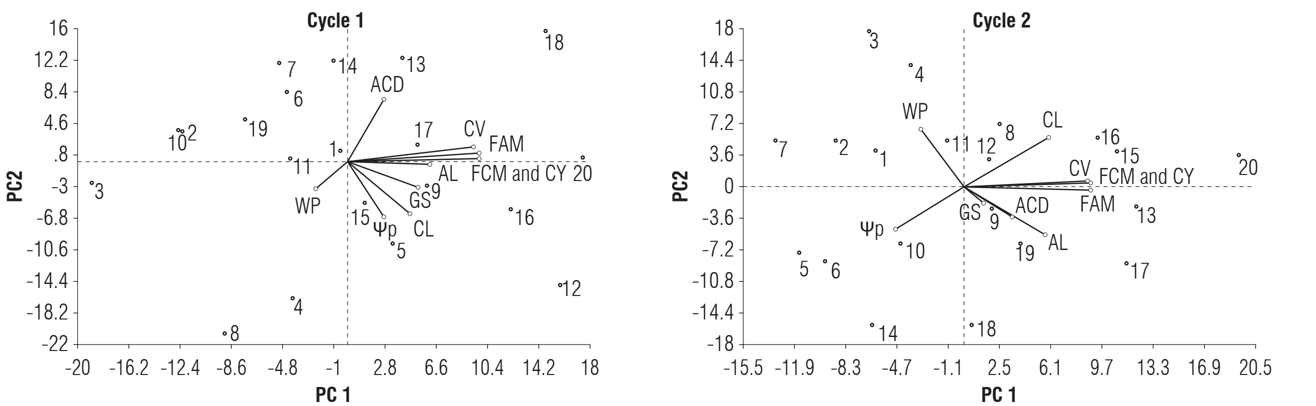
Since there is no 100% water absorption efficiency — due to losses from percolation, water redistribution in the soil, and areas with water deficit (Sousa & Assunção, 2021) — the 100% irrigation depth may not have provided sufficient water for the plants to reach their maximum productive potential. Additionally, the electrical conductivity of the soil also influenced the results.

Although the highest water productivity was observed for the lowest irrigation depth used (50% of ETc), the highest carrot yield in cycle 2 was achieved with application of 150% of ETc (Fig. 3). Plants exposed to water stress (application of smaller irrigation depths) suffer a decline in leaf water potential, stomatal conductance and CO_2 flux, impacting the accumulation of photoassimilates and crop yield (Hussain *et al.*, 2020; Fang *et al.*, 2021). This fact can also be explained by the increase in the concentration of abscisic acid (ABA) in the xylem of some species (Lamarque *et al.*, 2020; Ramachandran *et al.*, 2021).

Identification of patterns and trends

Figure 4 presents the principal component analysis (PCA) of the present study. The intensity of the association between the evaluated agronomic characteristics is indicated by the angle between the direction of their corresponding vectors, *i.e.*, the smaller the angle between the vectors, the greater the positive correlation between the represented characteristics. Thus, although there is a positive correlation, characteristics such as aboveground length, carrot volume, fresh aboveground mass and fresh carrot mass contributed more significantly to obtaining the high crop yield values in both cycle 1 and cycle 2 (Fig. 4).

In cycle 1, almost all characteristics evaluated had a positive association with crop yield, except water productivity, which displayed an inverse relationship with crop yield. This means that the highest crop yield value was achieved when water productivity was lower, and conversely, when water productivity was higher, crop yield decreased (Fig. 4). Most treatments that included irrigation lower than 100% of ETc (50 and 75%) were represented to the left of the central axis, with negative PC1 values (Fig. 4), showing a strong negative relationship with most of the variables of interest, demonstrating that these irrigation depths did not favor carrot yield. On the other hand, most treatments with water depths greater than 100% (125 and 150%) present positive PC values, indicating that higher irrigation depths provide higher crop yield values.



Treatment	Irrigation (% ETc)	Carrot cultivar	Treatment	Irrigation (% ETc)	Carrot cultivar	Treatment	Irrigation (% ETc)	Carrot cultivar	Treatment	Irrigation (% ETc)	Carrot cultivar
1	50	Brasília	6	75	Alvorada	11	100	Esplanada	16	125	Nantes
2	50	Alvorada	7	75	Esplanada	12	100	Nantes	17	150	Brasília
3	50	Esplanada	8	75	Nantes	13	125	Brasília	18	150	Alvorada
4	50	Nantes	9	100	Brasília	14	125	Alvorada	19	150	Esplanada
5	75	Brasília	10	100	Alvorada	15	125	Esplanada	20	150	Nantes

FIGURE 4. Principal component analysis (PCA) for carrot length (CL), aboveground length (AL), fresh aboveground mass (FAM), average carrot diameter (ACD), carrot volume (CV), green shoulder (GS), fresh carrot mass (FCM), crop yield (CY), water productivity (WP), and plant water potential (Ψp) as a function of different cultivars and irrigation depths in two cultivation cycles.

The preference for a 150% ETc level to obtain higher values of the studied characteristics is supported by Figure 3, which indicates that treatments 17, 18, 19, and 20 favored crop yield. This becomes even more evident in treatments 15, 16, and 17 and 20 as shown in Figure 4.

The irrigation depth of 150% ETc provided a higher carrot yield during the second cultivation. However, in practice, its use becomes unnecessary due to the lack of significant difference in cycle 1 (Tab. 3) and the marginal gain with 150% ETc replacement (Fig. 3). Therefore, a 100% ETc level is recommended for carrot cultivation under the conditions of this research.

Furthermore, although no statistical difference was observed between the cultivars based on the analysis of variance and mean test (Tab. 1), the principal component analysis (PCA) showed that almost all treatments containing the Brasília cultivar performed better, regardless of the irrigation depth, except for treatment 1 (Fig. 4), where the increased water stress mitigated the preference for this cultivar. This reveals that in conditions of reduced water supply, carrot varieties are unable to express their productive potential.

The observations in this study highlight the importance of choosing appropriate carrot cultivars for specific growing conditions, considering factors such as the protected environment, local climate and management practices. Furthermore, this study also offers valuable insights for farmers and agricultural professionals. With these results, producers can make more informed decisions when choosing the most suitable cultivars for their specific growing conditions, aiming to optimize performance and productivity. These findings have the potential to improve the efficiency and quality of carrot production, benefiting both producers and end consumers.

Conclusions

The Brasília carrot cultivar showed a tendency for better development in the protected environment studied. In contrast, the Esplanada cultivar proved to be less adapted to the environment, indicating the importance of choosing suitable cultivars for specific growing conditions.

All carrot cultivars were affected by stress caused by both excess and insufficient water. Irrigation depths greater than 100% of ETc provided better crop performance. However, the difference between 100% and 150% ETc was minimal, making the 100% ETc a viable choice for growing carrots under conditions similar to those of the present study.

Based on the findings of the present study, producers should choose the most appropriate carrot cultivars for specific growing conditions, considering the protected environment and management practices. Careful selection of the irrigation depth is also crucial to optimize crop performance. Our results offer valuable guidance for farmers in making informed decisions and can improve the efficiency and quality of carrot production.

Acknowledgments

We thank the Graduate Program in Agricultural Engineering (PPGEA) of the Federal University of Viçosa (Brazil) for supporting the researchers. This research was funded by Coordination for the Improvement of Higher Education Personnel—(CAPES)—Finance Code 001 and the National Council for Scientific and Technological Development—Brazil (CNPq)—Process 308769/2022-8.

Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

CMG, FCS, DJHS, and FFC – conceptualization; CMG, FCS, and FFC – methodology; CMG, FCS, and FFC – formal analysis; EDA, ABFG, and CMG – research development; DJHS, and FFC – resources; CMG, FCS, JTO, and FFC – writing and original draft preparation; JTO and FFC – writing, review and editing; DJHS and FFC – funding acquisition. All authors have read and agreed with the final version of the manuscript.

Literature cited

Abbas, K., Li, J., Gong, B., Lu, Y., Wu, X., Lü, G., & Gao, H. (2023). Drought stress tolerance in vegetables: The functional role of structural features, key gene pathways, and exogenous hormones. *International Journal of Molecular Sciences, 24*(18), Article 13876. https://doi.org/10.3390/ijms241813876

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56, FAO.

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Goncalves, J. L. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift, 22*, 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Alves, R. H., Carvalho, W. A. F., Fernandes, L. M., & Pereira, W. M. A. (2020). Emprego do pó de rocha MR-4 sobre a cultura da cenoura (*Daucus carota* L.). *Revista Cultivando o Saber, 13*, 29–50.

Bernardo, S., Mantovani, E. C., Silva, D. D., & Soares, A. A. (2019). *Manual de Irrigação* (9th ed.). Viçosa: Editora UFV.

Carvalho, A. D. F., Nogueira, M. T. M., Silva, G. O., Luz, J. M. Q., Maciel, G. M., & Rabelo, P. G. (2017). Seleção de genótipos de cenoura para caracteres fenotípicos de raiz. *Horticultura Brasileira*. *35*(1), 97–102. https://doi.org/10.1590/S0102-053620170115

Correia, C. C. S. A., Cunha, F. F., Mantovani, E. C., Silva, D. J. H., & Dias, S. H. B. (2020). Irrigation of radish cultivars in the region of Viçosa, Minas Gerais, Brazil. *Revista Ciência Agronômica, 51*(1), Article e20175643. https://doi.org/10.5935/1806-6690.20200011

Correia, C. C. S. A., Cunha, F. F., Mantovani, E. C., Silva, D. J. H., Dias, S. H. B., & Ferreira, T. S. (2019). Irrigation of arugula cultivars in the region of Zona da Mata Mineira. *Semina: Ciências Agrárias, 40*, 1101–1114. https://doi.org/10.5433/1679-0359.2019v40n3p1101

Cunha, F. F., Magalhães, F. F., Santos, O. F., Silva, T. R., Souza, E. J., & Godoy, A. R. (2016). Características agronômicas de cultivares de cenoura submetidas a diferentes lâminas de irrigação. *Agrarian, 9*(31), 84–95. https://ojs.ufgd.edu.br/index.php/agrarian/article/view/4238/3640

Cunha, F. F., Souza, I. P., Campos, W. O., Andrade Junior, V. C., & Magalhães, T. A. (2019). Agronomic performance of radish genotypes under different irrigation depths. *Engenharia Agricola*, *39*(2), 182–190. https://doi.org/10.1590/1809-4430-Eng.Agric.v39n2p182-190/2019

Drysdale, K. M., & Hendricks, N. P. (2018). Adaptation to an irrigation water restriction imposed through local governance. *Journal of Environmental Economics and Management, 91*, 150–165. https://doi.org/10.1016/j.jeem.2018.08.002

Embrapa – Empresa Brasileira de Pesquisa Agropecuária. (2003). *Cenoura Alvorada – Muito mais vitamina A. MAPA. Programação Visual* (1st ed.). EMBRAPA. https://ainfo.cnptia.embrapa.br/digital/bitstream/item/195017/1/digitalizar0175.pdf

Embrapa – Empresa Brasileira de Pesquisa Agropecuária. (2004). *Cenoura – Coleção plantar. Embrapa comunicação para transferência* (1st ed.). EMBRAPA

Embrapa – Empresa Brasileira de Pesquisa Agropecuária. (2005). *Cenoura Esplanada: Cultivar de Cenoura de Verão para Processamento. MAPA. Programação Visual* (1st ed.). EMBRAPA. https://ainfo.cnptia.embrapa.br/digital/bitstream/CNPH-2009/31472/1/bpd_7.pdf

Fang, Y., Leung, L. R., Wolfe, B. T., Detto, M., Knox, R. G., McDowell, N. G., Grossiord, C., Xu, C., Christoffersen, B. O., Gentine, P., Koven, C. D., & Chambers, J. Q. (2021). Disentangling the effects of vapor pressure deficit and soil water availability on canopy conductance in a seasonal tropical forest during the 2015 El Niño drought. *Journal of Geophysical Research: Atmospheres, 126*(10), Article e2021JD035004. https://doi.org/10.1029/2021JD035004

Filgueiras, R., Ferreira, L. B., & Cunha, F. F. (2022). Digital irrigation. In D. M. Queiroz, D. S. M. Valente., F. A. C. Pinto, A. Borém, & J. K. Schueller (Eds.), *Digital agriculture* (pp. 157–172). Springer. https://doi.org/10.1007/978-3-031-14533-9_10

Gómez, C., Currey, C. J., Dickson, R. W., Kim, H., Hernández, R., Sabeh, N. C., Raudales, R. E., Brumfield, R. G., Laury-Shaw, A., Wilke, A. K., Lopez, R. G., & Burnett, S. E. (2019). Controlled environment food production for urban agriculture. *HortScience*, *54*(9), 1448–1458. https://doi.org/10.21273/hortsci14073-19

Guimarães, C. M., Cunha, F. F., Silva, F. C. S., Araújo, E. D., Guimarães, A. B. F., Mantovani, E. C., & Silva, D. J. H. (2019). Agronomic performance of lettuce cultivars submitted to different irrigation depths. *PLoS ONE, 14*(12), Article e0224264. https://doi.org/10.1371/journal.pone.0224264

Hussain, T., Koyro, H. W., Zhang, W., Liu, X., Gul, B., & Liu, X. (2020). Low salinity improves photosynthetic performance in *Panicum antidotale* under drought stress. *Frontiers in Plant Science, 11*, Article 481. https://doi.org/10.3389/fpls.2020.00481

Kwiatkowski, C. A., Pawłowska, M., Harasim, E., & Pawłowski, L. (2023). Strategies of climate change mitigation in agriculture plant production – A critical review. *Energies*, *16*(10), Article 4225. https://doi.org/10.3390/en16104225

Lamarque, L. J., Delzon, S., Toups, H., Gravel, A-I., Corso, D., Badel, E., Burlett, R., Charrier, G., Cochard, H., Jansen, S., King, A., Torres-Ruiz, J. M., Pouzoulet, J., Cramer, G. R., Thompson, A. J., & Gambetta, G. A. (2020). Over-accumulation of abscisic acid in transgenic tomato plants increases the risk of hydraulic failure. *Plant, Cell & Environment, 43*(3), 548–562. https://doi.org/10.1111/pce.13703

Li, Y., Li, J., Gao, L., & Tian, Y. (2018). Irrigation has more influence than fertilization on leaching water quality and the potential environmental risk in excessively fertilized vegetable soils. *PLoS ONE, 13*(9), Article e0204570. https://doi.org/10.1371/journal.pone.0204570

Luz, J. M. Q., Silva Júnior, J. A., Teixeira, M. S. S. C., Silva, M. A. D., Severino, G. M., & Melo, B. (2009). Desempenho de cultivares de cenoura no verão e outono-inverno em Uberlândia-MG. *Horticultura Brasileira, 27*(1), 96–99. https://doi.org/10.1590/S0102-05362009000100019

Martínez-Gómez, P., Devin, S. R., Salazar, J. A., López-Alcolea, J., Rubio, M., & Martínez-García, P. J. (2021). Principles and prospects of *Prunus* cultivation in greenhouse. *Agronomy, 11*(3), Article 474. https://doi.org/10.3390/agronomy11030474

Massa, D., Magán, J. J., Montesano, F. F., & Tzortzakis, N. (2020). Minimizing water and nutrient losses from soilless cropping in southern Europe. *Agricultural Water Management, 241*, Article e106395. https://doi.org/10.1016/j.agwat.2020.106395

Mustafa, M., Szalai, Z., Ertsey, A. D., Gál, I., & Csambalik, L. (2022). Conceptualizing multiple stressors and their consequences in agroforestry systems. *Stresses*, *2*(3), 242–255. https://doi.org/10.3390/stresses2030018

Nasir, J., Ashfaq, M., Baig, I. A., Punthakey, J. F., Culas, R., Ali, A., & Hassan, F. (2021). Socioeconomic impact assessment of water resources conservation and management to protect groundwater in Punjab, Pakistan. *Water, 13*(19), Article 2672. https://doi.org/10.3390/w13192672

Nikolaou, G., Neocleous, D., Katsoulas, N., & Kittas, C. (2019). Irrigation of greenhouse crops. *Horticulturae, 5*(1), Article 7. https://doi.org/10.3390/horticulturae5010007

Ramachandran, P., Augstein, F., Mazumdar, S., Van Nguyen, T., Minina, E. A., Melnyk, C. W., & Carlsbecker, A. (2021). Abscisic acid signaling activates distinct VND transcription factors to promote xylem differentiation in *Arabidopsis*. *Current Biology, 31*, 3153–3161. https://doi.org/10.1016/j.cub.2021.04.057

Resende, G. M., & Braga, M. B. (2014). Produtividade de cultivares e populações de cenoura em sistema orgânico de cultivo. *Horticultura Brasileira, 32*(1), 102–106. https://doi.org/10.1590/S0102-05362014000100017

Resende, G. M., & Cordeiro, G. G. (2007). Yield of carrot as affected by water quality and soil conditioning in the São Francisco valley. *Caatinga*, *20*(1), 100–104. https://www.alice.cnptia.embrapa.br/alice/handle/doc/158134

Ribeiro, A. C., Guimarães, P. T. G., & Alvarez, V. V. H. (Eds.). (1999). *Recomendações para o uso de corretivos e fertilizantes em Minas Gerais - 5ª aproximação*. Viçosa: CFSEMG. https://www.bdpa.cnptia.embrapa.br/consulta/busca?b=ad&id=324081&biblioteca=vazio&busca=autoria:%22ALVAREZ%20V.,%20V.H.%20(Ed.).%22&qFacets=autoria:%22ALVAREZ%20V.,%20V.H.%20(Ed.).%22&sort=&paginacao=t&paginaAtual=1

Rosińska, A., Andrzejak, R., & Kakkerla, V. (2023). Effect of osmopriming with melatonin on germination, vigor and health of *Daucus carota* L. seeds. *Agriculture*, *13*, Article 749. https://doi.org/10.3390/agriculture13040749

Santos, P. M., & Silva, T. E. S. (2020). O uso da internet das coisas para o desenvolvimento sustentável da agricultura. *Revista Multidisciplinar do Sertão, 2*(1), 13–24. https://revistamultisert1.websiteseguro.com/index.php/revista/article/view/217

Schmid, C., Sharma, S., Stark, T. D., Günzkofer, D., Hofmann, T. F., Ulrich, D., Dunemann, F., Nothnagel, T., & Dawid, C. (2021). Influence of the abiotic stress conditions, waterlogging and drought, on the bitter sensometabolome as well as agronomical traits of six genotypes of *Daucus carota*. *Foods*, *10*(7), Article 1607. https://doi.org/10.3390/foods10071607

Scholander, P. F., Hammel, H. T., Hemmingsen, E. A., & Bradstreet, E. D. (1964). Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plants. *Proceedings of the National Academy of Sciences*, *52*(1), 119–125. https://doi.org/10.1073/pnas.52.1.119

Silva, T. S. S., Silva, W. E., Santos Neto, A. L., Ferro, M. G. F., Silva, D. A. O., & Silva, R. R. (2019). Coriander production submitted to different spatial arrangements in the State of Alagoas. *Revista Ambientale, 11*(1), 46–55. https://doi.org/10.48180/ambientale.v11i1.112

Soares, I. A. A., Freitas, F. C. L., Negreiros, M. Z., Freire, G. M., Aroucha, E. M. M., Grangeiro, L. C., Lopes, W. A. R., & Dombroski, J. L. D. (2010). Interferência das plantas daninhas sobre a produtividade e qualidade de cenoura. *Planta Daninha, 28*(2), 247–254. https://doi.org/10.1590/S0100-83582010000200003

Sousa, F. A., & Assunção, H. F. (2021). Capacidade de armazenamento de água no solo (CAD) e características físicas dos solos na avaliação da distribuição da água das chuvas na alta bacia do Ribeirão Santo Antônio. *Revista Brasileira de Geografia Física, 14*(6), 3635–3647. https://doi.org/10.26848/rbgf.v14.6.p3635-3647

Teixeira, P. C., Donagemma, G. K., Fontana, A., & Teixeira, W. G. (2017). *Manual de métodos de análise de solo* (3rd ed.). Brasília, DF.

Zhao, Y. H., Deng, Y. J., Wang, Y. H., Lou, Y. R., He, L. F., Liu, H., Li, T., Yan, Z. M., Zhuang, J., & Xiong, A. S. (2022). Changes in carotenoid concentration and expression of carotenoid biosynthesis genes in *Daucus carota* taproots in response to increased salinity. *Horticulturae, 8*(7), Article 650. https://doi.org/10.3390/horticulturae8070650