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Using infrared thermometry to manage irrigation water for some vegetable crops

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Abstract

Measurement of the canopy temperature using infrared thermometry has been extensively studied to understand plant water status and to schedule crop irrigation. Many regions globally have insufficient water supply resulting in reduced crop yields. Thus, this work investigated the best treatments to cultivate kohlrabi using three amounts of water during growth (T1 = 180 mm; T2 = 270 mm; T3 = 360 mm) and three distances between plants (S1 = 0.50 m; S2 = 0.75 m; S3 = 1.00 m). The amount of water was estimated related to canopy temperature (Tc), air temperature (Ta) and vapor pressure deficit (VPD). The results indicated that there was an inverse relationship between Tc and water quantities, where Tc decreased 3ºC from 28ºC to 25ºC under T3 compared to T1. Furthermore, VPD was (2.18 KPa) under T1 and S3, with Tc – Ta equal to 1.6ºC. VPD decreased from 1.78 KPa to 1.64 KPa when the leaf area index (LAI) increased from 0.6 m^2/m^2 to 1.2 m^2/m^2 for T2. Thus, the highest yield (4,540 kg/fed) was observed with T2 when the VPD of the kohlrabi flower stage was 1.73KPa and Tc – Ta was -0.453°C. Clearly, by increasing the distance between plants from 0.5 m to 1.0 m, the yield decreased (233.5 kg/fed). Finally, the models VPD = 1.826 + [0.00752 × LAI] + [0.2058 × (Tc – Ta)] and T = 45.1704 – [16.213 × VPD] indicated that the total water applied (T) for kohlrabi depended on four parameters (LAI, Tc, Ta and VPD).

Introduction

The globally growing demand for water has ushered in the need for its efficient and equitable utilization in all areas, especially for agriculture which is considered the largest consumer of water (Noemi et al., 2015). In addition, in barren and semi- barren regions, the success of sustained agriculture depends entirely on the availability of water, making the effective use of irrigation water and crop water demand vital factors to expanding the cultivated area. Thus, irrigation water management depends on critical factors, such as soil moisture and crop evapotranspiration which can be determined from climatic parameters. However, estimating evapotranspiration requires a large climatic dataset, which is rarely available

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and not readily utilized by smallholder farmers. Estimating the water requirement for crops using soil moisture needs many soil moisture measurements from many locations. Nevertheless, even when applied, this method has not provided accurate data about crop water requirements (Georgea et al., 2000). Furthermore, the adoption of deficit irrigation to rationalize water usage has not been successful in many areas because there is no simple method available to guide the implementation of deficit irrigation.

Canopy temperature (Tc) can be rapidly measured for monitoring the reaction of a plant to water stress (Idso et al., 1981; Jackson et al., 1981). The behaviour of Tc under stress or non-stress conditions provides clues regarding yield performance and crop water status during drought. For example, when plants suffer from a shortage of water, stomata shut and this leads to interrupted energy dissipation; consequently, the leaf temperature increases Jackson (1982). On the other hand, genetically controlling Tc could be profitable for selecting crop varieties that can avoiding water stress (Blum et al., 1982). In addition, using Tc for measurements over a large area can utilize geo-referenced mapping to reflect crop water stress and yield predictions (O'Shaughnessy et al., 2011). For example, Sadler et al. (2002) used 26 infrared canopy temperature sensors to help estimate the canopy energy balance under a center-pivot irrigation system and for surveillance of irrigation uniformity in a field crop. Wanjura and Upchurch (1997) applied a temperature time-threshold model in irrigation water management for cotton.

Tc, air temperature (Ta) and atmospheric vapor pressure deficiency (VPD) are vital variables which impact on crop water use efficiency (Braunworth, 1989). Gardner and Shock (1989) assumed that 1–6 Kpa for the air vapor pressure deficit (AVPD) was sufficient as a baseline for use in numerous locations. Furthermore, AVPD and subtracting air temperature (Ta) from the canopy temperature (Tc) were applied to develop a crop water stress index (CWSI) by Idso et al. (1982). The VPD reflects plant efficiency and how the plant deals with its internal energy balance and the external environment. Kjelgaard et al. (1996) developed a sophisticated a model for estimating daily evapotranspiration rates with potential implementation to estimate water requirements for irrigation as a sequel to CWSI measurements that indicated when to irrigate. Joint techniques can be utilized to construct an irrigation schedule that uses much of the same data.

On the other hand, water requirement is the predominant factor affecting crop development (Yamaguchi-Shinozaki et al., 2002). Growth and photosynthesis are slightly or completely suppressed by water shortage (Kramer and Boyer, 1995), generally leading to reduced crop yields. Plant damage caused by water shortage varies, depending on the level and period of the shortage and other environmental factors (Glantz, 1994) Thus, plants have evolved mechanisms for adaptation and survival during water deficit (de Carvelho, 2008).

Consequently, water use efficiency (WUE) is a helpful measure in the implementation of a successful irrigation system regarding crop production (Alghariani, 2002) to estimate the proportion of applied water effectively used by a crop. WUE is often determined using the proportion between the production of crop (biomass or grain yield) and the quantity of water consumed by the crop (comprehensive crop transpiration, rainfall, or irrigation water applied) (Zhang and Oweis, 1999). WUE can be used as a reference for crop production and water productivity (Pereira et al., 2002).

Clearly, a positive outcome can be achieved by controlling the relationship among the factors of an agricultural system, especially canopy temperature, the amount of irrigation water, vapor pressure deficit, plant density and environmental elements. Thus, this study investigated irrigation water management based on three treatments using average water amounts and three treatments for distance between plants and their influence on the factors of an agricultural system growing kohlrabi to develop a simple mathematical relationship between the water supplied and (Tc – Ta), LAI and VPD.

Materials and Methods

The research was conducted in the Suez Canal University-Faculty of Agriculture located in the Ismailia governorate (30°37'10.91"N; 32°16'1.33"E) and was established in early February 2019. The soil had a sandy texture and was neither calcareous nor saline, with a soil conductivity of 1.37dS/m. Silt and clay contents were very low (3.2% and 1.2%, respectively). Field capacity (5.6 %) and available water (4.5%) were both very low. Water samples were analyzed based on analytical procedures for pH, ion composition and electrical conductivity (American Public Health Association et al., 1992). The chemical analysis for the irrigation water is given in Table 1.

The site was in a barren area with a Mediterranean climate. The annual rainfall was 29 mm/year and the elevation was approximately 30m above sea level. Meteorological data recorded at the local meteorological weather station of average climatic parameters are provided in Table 2 for relative humidity, temperature, evapotranspiration, wind speed and sunshine. The Penman-Monteith equation was used to determine reference crop evapotranspiration (ET_o), according to Allen et al. (1998).

The total water applied was estimated according to Seager et al. (2015) using crop coefficient (Kc) factors (Table 3) and ET_o to determine the crop water requirement and total water applied as described in Equations 1–3:

$$ET_c = ET_o \times K_c \quad (1)$$

where ET_c is the crop Evapotranspiration and ET_o is the reference evapotranspiration, both measured in millimeters per day, and K_c is the crop coefficient.

$$IR_n = ET_c - P_{eff} \quad (2)$$

where IR_n is the net irrigation requirement ET_c is the crop evapotranspiration and P_{eff} is the effective rainfall, all measured in millimeters per day.

$$IR_t = IR_n/E_a \quad (3)$$

where IR_t is the total water applied IR_n is the net irrigation requirement, both measured in millimeters per day, and E_a is the modern irrigation system efficiency (for drip 90%) (Phocaides, 2007).

The total water quantity for Kohlrabi was 360 mm a self-trickling irrigation system line (4 L/50 cm/hr) under pressure (1.2 Kg/cm^2) was used to deliver three amounts of water (T1, 180 mm; T2, 270 mm; T3, 360 mm) for kohlrabi. The sub-blot factor was distance between plants in three treatments (S1, 0.5 m; S2, 0.75 m; S3, 1.0 m). The kohlrabi seeds were grown in trays for 2 wk and irrigated regularly in the greenhouse until the plants had reached an appropriate size. Subsequently, the seedlings were transplanted in the field on 2 February.

Measurements and calculations

Vapor pressure deficit

The vapor pressure deficit (VPD) was calculated related to relative humidity, air temperature, and leaf temperature and measured in kilopascals (Seager et al., 2015) according to Equation 4:

$$VPD = VP_{sat} - VP_{air} \quad (4)$$

where VP_{sat} = saturated vapor pressure; VP_{air} = actual air vapor pressure.

The plant leaf temperature is necessary for estimating VP_{sat} and was measured using an infrared temperature gun

Table 1 Chemical analysis of irrigation water

pH	EC (dS/m)	Cations (meq/L)				Anions(meq/L)				SAR
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$(CO_3)^{2-}$	$(HCO_3)^{1-}$	Cl^{-1}	$(SO_4)^{2-}$	
7.34	1.18	2.8	0.6	8.2	0.2	0	2.92	6.83	2.05	6.3

EC = electrical conductivity; SAR = Sodium adsorption ratio

Table 2 Meteorological data at experimental site

Month	Precipitation	Temp. max	Temp. min	Humidity	Sunshine	Wind speed	ET_o
	mm/mth	°C	°C	%	hr	m/s	mm/d
Feb	0	22.7	13.5	57.2	8	2.8	3.5
March	0	26.9	15.2	56.3	8.7	2.8	4.8
April	0	28.8	19.2	48.7	10.1	2.8	6.0

Wind speed measured at 2 m above ground level; ET_o = reference evapotranspiration

Table 3 Average crop parameters for kohlrabi

Parameter	Initial	Crop development	Mid-season	Late season	Total
Days	20	30	15	10	75
Crop coefficients	0.7	1.05	1.05	0.95	

(UNI-T UT300C). This device consisted of an infrared thermometer designed for measuring the surface temperature within a range from -20°C to 400°C. The leaf temperature was recorded throughout the day starting at 1000 hours until 1600 hours. Equation 5 was used to calculate VP_{sat}:

$$VP_{sat} = \frac{610.7 * 10^{\left(\frac{7.5T}{237.3+T}\right)}}{1000} \quad (5)$$

where T is the leaf temperature measured in degrees Celsius.

The air temperature and relative humidity are required parameters to measure VP_{air}, as shown in Equation 6:

$$VP_{air} = \frac{610.7 * 10^{\left(\frac{7.5Ta}{237.3+Ta}\right)}}{1000} * \frac{RH}{100} \quad (6)$$

where Ta is the air temperature measured in degrees Celsius and RH is the relative humidity measured as a percentage.

Leaf area index

The leaf area index (LAI) was calculated according to Kar et al. (2006), as shown in Equation 7:

$$LAI = 0.75\ x\ p\ x \left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}(L_{iJ}\ x\ B_{iJ})}{m}\right) \quad (7)$$

where LAI is the leaf area index, measured in square meters per square meter, *p* is the plant density, measured in plants per square meter, m = is the number of measured plants, N is the number of leaves on the plant, L_{ij} is the leaf length, measured in meters and B_{ij} is the leaf width, measured in meters.

Modeling and statistical analysis:

The COSTAT 3.03 System software was used to analyze data based on a two way ANOVA under a split plot design using Duncan's honest significant difference test at $p < 0.05$. The simple regression model with predictor variables X1…Xp was described using Equation 8:

$$y = B_0 + B_1X_1 + \ldots B_nX_n + z \quad (8)$$

Where variable y (the response or dependent variable) depends on other variables $X_{(1..n)}$ (the independent or predictor variables, B_0 is the intercept, $B_{1\text{-}P}$ is the slope parameter and the variability of the error (*z*) is constant for all values.

Results and Discussion

Canopy temperature

Tc varied with the different treatments (Fig. 1). In addition, the distance between plants had a significant influence on Tc. For example, the mean value for Tc was 26.89°C in treatment S3, which was significantly different compared to treatments S2 and S3 that had lower values of 26.46°C and 26.11°C, respectively. There was a positive relationship between Tc and the distance between plants, with a plant density increase from 1.0 m to 0.5 m reducing the Tc by 0.78°C. There was an inverse relations hip between Tc and water quantities that agreed with Ćosić et al. (2018) who reported that the irrigation regime had a very significant influence on the canopy temperature of pepper and tomato, with the higher the level of irrigation, the lower the temperature. Tc was significantly higher (28.06°C)

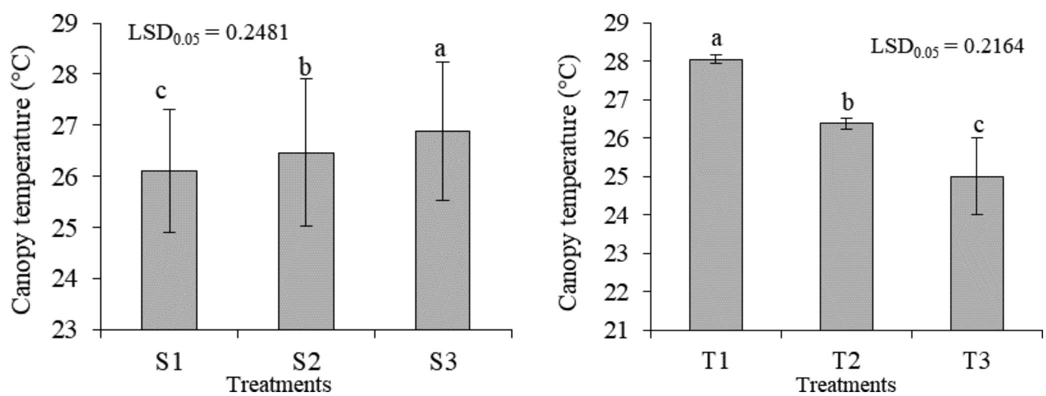

Fig. 1 Influence of distance between plants and water amount on canopy temperature, where S1 = distance of 0.50 m, S2 = distance of 0.75 m, S3 = distance of 1.00 m, T1 = amount of 180 mm, T2 = amount of 270 mm, T3 = amount of 360 mm, LSD = least significant difference and error bars indicate ± SD; Different lowercase letters above bars indicate significant ($p < 0.05$) differences.

with a low amount of water (T1). However, with a high amount of water (T1), Tc decreased by 3°C to 25°C, compared to T1. These results may have been related to the canopy temperature under stressed and non-stressed situations, as indications of crop water status and yield production pending drought conditions (Jackson et al., 1981). In addition, Boari et al. (2015) reported that a reduction in the canopy temperature of kaolin plants under stress due to water deficit or soil salinity. The better the water supply, the lower the leaf temperature because transpiration was unhindered. Conversely, air temperature and water stress led to an increase in leaf temperature (Russo and Díaz-Pérez, 2005).

Clearly, both the distance between plants and the amount of water had significant impacts on canopy temperature but in different ways. Thus, Tc decreased with a reduction in the distance between plants or an increase in the amount of water.

Leaf area index

The LAI for kohlrabi varied among the treatments, as illustrated in Fig. 2. For example, the highest value for LAI (1.4 m^2/m^2) was for S1 while under S2 and S3 the values were 0.97 m^2/m^2 and 0.706 m^2/m^2, respectively. Similarly, the amount of water had a significant influence on LAI, with T3 having the highest LAI value (1.2 m^2/m^2). However, there was no significant difference under T1 and T2 that had LAI values of 1 m^2/m^2 and 0.86 m^2/m^2, respectively. Notably, T3 had a different influence on LAI under S1 compared to T1 and T3, with the value of LAI under T3 being higher than for T1 and T2 by 33% and 14%, respectively. Importantly, the LAI value was high with S1 and T3 because kohlrabi needs cultivation in a dense layout with a good amount of water so that the plant's physiological processes during the different growth stage are optimized. This agreed with Streck et al. (2014) who reported that decreasing the distance between plants produced the highest LAI and leaf development (phyllochron) increase.

Vapor pressure deficit

The VPD has been widely recognized as the evaporative driving force for water transport, indicating the potential to reduce plant water consumption and to improve water productivity by regulating VPD (Zhang et al., 2017). There was a liner relationship between VPD, Tc and Ta (Fig. 3). VPD (2.18 KPa) was highest under T1 and S3 with an average increase of 1.6°C in Tc compared to Ta.

However, the VPD reduced to 1.5 KPa when the value for Tc – Ta was -1.5°C under T3 and S3. The VPD reduced when Tc decreased with the same amount of water; however, with a low amount of water, the plants suffered from water stress, leading to an increase in the VPD, which was in agreement with Zhang et al. (2017). On the other hand, the mean average value for VPD increased from 1.67 KPa to 1.83KPa when the distance between plants increased from 0.5 m to 1.0 m under various water quantities. As the VPD increased, the full potential of evapotranspiration was utilized and the plants cooled down resulting in a negative value for Tc – Ta (Nielsen, 1990).

Whilst in the flower stage, the plants were robust, the flowers were sensitive to various issues with the need to avoid excess humidity. The ideal VPD for the flower stage is closer to the top end of the range (1.2–1.5kPa), according to Konopacki et al. (2018).

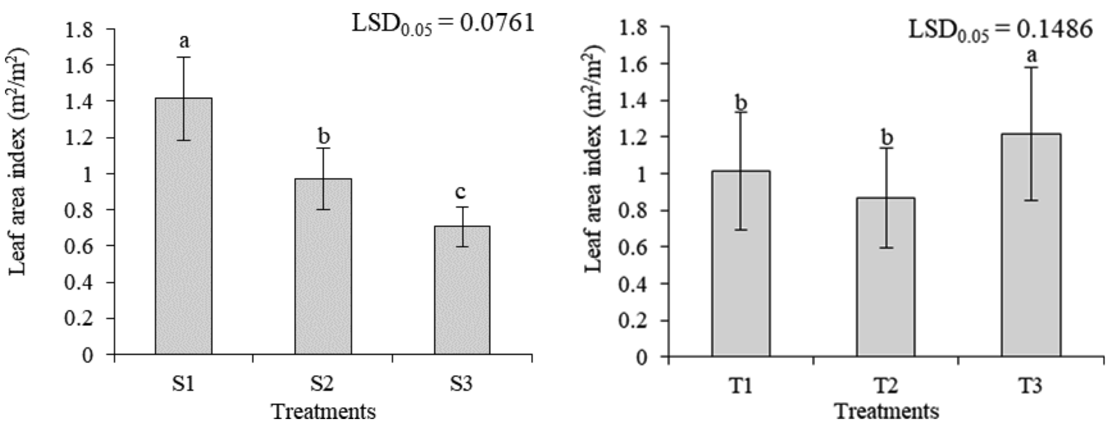

Fig. 2 Leaf area index for kohlrabi under various distances between plants and water amounts, where S1 = distance of 0.50 m, S2 = distance of 0.75 m, S3 = distance of 1.00 m, T1 = amount of 180 mm, T2 = amount of 270 mm, T3 = amount of 360 mm, LSD = least significant difference and error bars indicate ± SD; Different lowercase letters above bars indicate significant ($p < 0.05$) differences

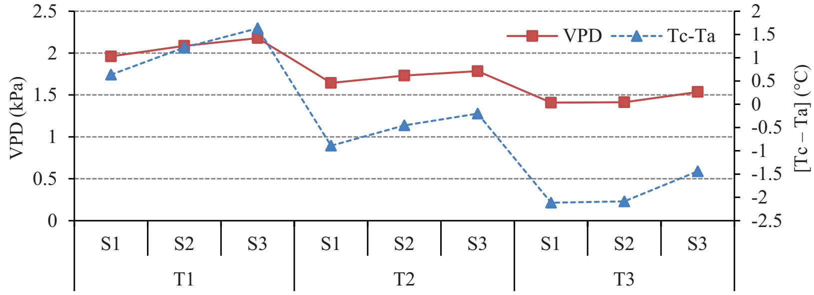

Fig. 3 Relationship between vapor pressure deficit (VPD) and canopy temperature minus air temperature (Tc – Ta) under various distances between plants and water amounts, where S1 = distance of 0.50 m, S2 = distance of 0.75 m, S3 = distance of 1.00 m, T1 = amount of 180 mm, T2 = amount of 270 mm,T3 = amount of 360 mm

On the other hand, the LAI had a significant inverse relationship with VPD, with the LAI increasing as the VPD decreased under various treatments (Fig. 4). For example, the VPD decreased from 1.78 KPa to 1.64 KPa when the LAI increased from 0.6 m^2/m^2 to 1.2 m^2/m^2, respectively, under T2. The highest value for the VPD (2.18 KPa) was when the LAI was 0.69 m^2/m^2 under the low amount of water (T1). In contrast, the lowest value for VPD (1.408 KPa) was when the LAI was 1.6 m^2/m^2, with high levels for plant density (S1) and the amount of water (T3). Clearly, the plant density had a significant impact on VPD, as increasing the distance between plants decreased the LAI and consequently increased the VPD.

As the VPD increases, evapotranspiration also increases as the air has an increased capacity to hold water vapor, creating a larger potential gradient across the leaf-air and soil-air boundaries (Garratt, 1992). This increased transpiration in low LAI canopies is probably the cause of the observed trend in specific humidity, with high LAI canopies having a smaller specific humidity than low LAI canopies (Law et al., 2001).

A model is a schematic representation of a system or mimics a set of equations, which represents the behavior of a system (Murthy, 2003). Thus, there was a significant response between both LAI and Tc and VPD with R^2 values of more than 0.9, as shown in Equations (9) and (10):

$$VPD = 1.826 + [0.00752 \times LAI] + [0.2058 \times (Tc - Ta)] \quad (9)$$

$$T = 45.1704 - [16.213 \times VPD] \quad (10)$$

where VPD is the vapor pressure deficit measured in kilopascals, LAI is the leaf area index measured in square meters per meter, Tc and Ta are the leaf temperature and air temperature respectively, both measured in degrees Celsius and T is the total water applied [m3/fed /day].

Hence, these relationships could be used to determine the total water applied per day depending on the VPD and knowing the values for LAI, Ta and Tc for kohlrabi under such conditions.

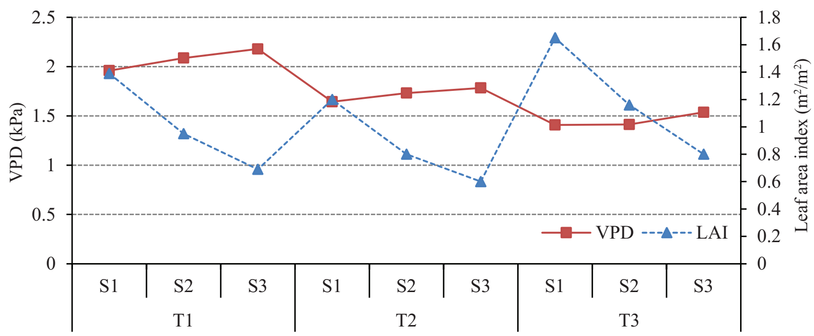

Fig. 4 Relationship between vapor pressure deficit (VPD) and leaf area index (LAI) under various distances between plants and water amounts, where S1 = distance of 0.50 m, S2 = distance of 0.75 m, S3 = distance of 1.00 m, T1 = amount of 180 mm, T2 = amount of 270 mm, T3 = amount of 360 mm

Growth parameters and yield

Table 4 indicates that there was a significant influence of water quantity and distance between plants on all the plant parameters (plant length [PL] - number of leaves [NL]) and yield production. The highest mean values for PL and NL were 35.16 cm and 19.6, respectively, with the amount of water under T2. Consequently, the highest yield production (4,540 kg/fed) was observed under T2 compared to the other water quantities (T1 and T3). On the other hand, plant distance had a considerable influence on the yield and growth parameters where the distance between plants in S1 produced the highest mean value for yield, PL and NL (4,253.4 kg/fed, 33.3 cm and 20.3, respectively). In contrast, the lowest values (4,019.88 kg/fed, 31.3 cm and 18 for the yield and growth parameters, respectively) were observed under S3, showing a clear negative response to increasing the distance between the kohlrabi plants, with increasing the plant distance from 0.5 m to 1.0 m decreasing the yield by 233.5 kg/fed in conjunction with decreases in the plant length and number of leaves. Furthermore, the amount of water under T2 provided better yield and growth parameters compared to the amounts of water under T1 and T3, perhaps because the VPD increased by increasing the plant distance under S3 and the reduced amount of water under T1 (Fig. 5). However, under S1 and T2, the VPD (1.6 KPa) resulted in a significant improvement in the growth parameters and a significant increase in leaf number, plant length and yield compared to the other treatments because; a small VPD meant that peak growth rates were not achieved and problems such as mold or root rot could become an issue. On the other hand, with a large VPD, the plant stomata will close in an attempt to limit transpiration which can result in issues like tip burn and leaf curl (Breit et al., 2019).

In addition, leaf dehydration was alleviated in treatment with a low VPD by suppressing the evaporative driving force and reducing the transpiration rate. Consequently, a decline in leaf water potential was effectively prevented and a relatively homeostatic water status was achieved in the plants grown under a low VPD (Novick et al., 2016)

Table 4 Influence of different treatments on plant length, number of leaves and yield

Clause	Treatment					
	S1	S2	S3	T1	T2	T3
Plant length (cm)	33.3±2.73^{a}	32.88±2.63^{a}	31.3±3.49^{b}	33.55±1.31^{b}	35.16±0.86^{a}	28.83±1.5^{c}
$LSD_{0.05}$	0.9582			0.4540		
Number of leaves	20.3±1.37^{a}	19.6±1.13^{a}	18±1.22^{b}	18.6±1.02^{b}	19.6±1.04^{a}	19.6±2.1^{a}
$LSD_{0.05}$	1.0826			0.4362		
Yield (Kg/feddan)	4253.4±497.21^{a}	4126.22±602.16^{b}	4019.88±415.4^{c}	4365.1±193^{b}	4540±76^{a}	3476.4±184^{c}
$LSD_{0.05}$	63.497			59.06		

Distances between plants: S1 = 0.50 m, S2 = 0.75 m, S3 = 1.00 m; Water amounts: T1 = 180 mm, T2 = 270 mm, T3 = 360 mm; LSD = least significant difference

Mean ± SD values superscripted with different lowercase letters indicate significant ($p < 0.05$) differences among means within each treatment category.

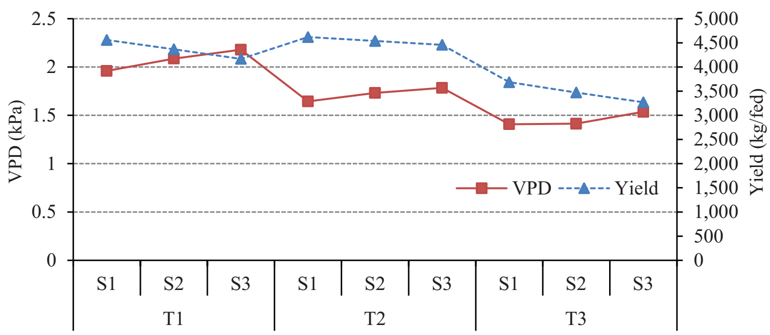

Fig. 5 Relationship between vapor pressure deficit (VPD) and yield under various distances between plants and water amounts, where S1 = distance of 0.50 m, S2 = distance of 0.75 m, S3 = distance of 1.00 m, T1 = amount of 180 mm, T2 = amount of 270 mm,T3 = amount of 360 mm

Hence, Equation (11) can be used to determine the yield for kohlrabi depending on the VPD and knowing the total water applied in the season:

$$Yield = 6495.6 – [384.9 \times VPD] – [1.34 \times T_s] \quad (11)$$

where Yield = kohlrabi production (Kg/feddan)VPD = the vapor pressure deficit [KPa] Ts is the total water applied in the growing season [mm]

Using infrared thermometers to measure the canopy or leaf temperatures for kohlrabi can be beneficial to facilitate irrigation management. Using this approach, the current study determined the best treatments to cultivate kohlrabi crop considering three amounts of water (T1= 180 mm, T2 = 270 mm, T3 = 360 mm) and three distances between plants (S1 = 0.50 m, S2 = 0.75 m, S3 = 1.00 m). The results indicated that changing the distance between plants form 1.0 m to 0.5 m reduced the canopy temperature by 0.78°C. On the other hand, there was an inverse relationship between Tc and the water quantity, where increasing the amount of water reduced Tc, specifically, a high amount of water (T3) decreased Tc by 3°C to 25°C compared to T1. Furthermore, the highest VPD (2.18 KPa) was recorded under T1 and S3 with an increase in the leaf temperature compared to the air temperature on average of 1.6°C. The VPD decreased from 1.78 KPa to 1.64 KPa when the LAI increased from 0.6 m^2/m^2 to 1.2 m^2/m^2 under T2. Thus, the highest value for yield production (4,540 kg/fed) was observed under T2 compared to the other water quantities (T1 and T3). This yield resulted from a VPD at the kohlrabi flower stage of 1.73KPa and a value of Tc – Ta of -0.453°C. Clearly, the distance between plants had a negative response on kohlrabi yield, as an increase from 0.5 m to 1.0m decreased the yield by 233.5 kg/fed in conjunction with decreases in the plant length and the number of leaves. Finally, the models VPD = 1.826 + [0.00752 × LAI] + [0.2058 × (Tc – Ta)] and T = 45.1704 – [16.213 × VPD] could be used to help to calculate the total water applied for kohlrabi depending on four parameters (leaf area index, leaf temperature, air temperature and vapor pressure deficit VPD). In addition, using infrared thermometry helped to clarify whether the plant was being irrigated with the ideal amount of water based on the models.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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