CORRELATION BETWEEN THERMAL INDICES OF MELON UNDER SUSTAINED IRRIGATION (SI) AND REGULATED DEFICIT IRRIGATION (RDI)

CORRELAÇÃO ENTRE ÍNDICES TÉRMICOS DO MELOEIRO SOB IRRIGAÇÃO SUSTENTADA (SI) E POR DÉFICIT REGULADO (RDI)

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ABSTRACT: The aim of this study was to present correlations between thermal indices in the response of the flowering and fruiting phase (phase III) of yellow melons subjected to sustained deficit irrigation (SI) and controlled deficit irrigation (RDI). The experimental design adopted was a randomized block design with 4 replications of 9 irrigation treatments, 4 referring to SI (T1 - 125%, T2 - 100%, T3 - 75%, T4 - 50%) and 5 characterizing RDI [T5 (75% in phases I and IV and 100% in phases II and III); T6 (50% in phase I, 100% in phase II and 75% in phases III and IV); T7 (100% in phase I, 75% in phases II and III and 50% in phase IV); T8 (50% in phase II and 100% in the others); and T9 (75% in phase I, 100% in phase III and 50% in phases III and IV)]. The thermal indices ($\Delta T_{canopy-air}$, CWSI and IG) were calculated from thermographic images captured at 8:00 am, 12:00 pm and 4:00 pm. The thermal indices showed high correlations ($R^2 > 0.7$) with each other at all the times assessed. In the context of irrigation management, the thermal indices evaluated can be used for the basic question of "when to irrigate?", with $\Delta T_{canopy-air}$ being the most practical, as it does not require the reference temperatures T_{dry} and T_{wet}.

Keywords: *cucumis melo L.*, infrared thermography, "When to irrigate?", water stress.

RESUMO: Esse trabalho teve como objetivo apresentar correlações entre índices térmicos na resposta da fase de floração e frutificação (fase III) do melão amarelo submetido a irrigação por déficit sustentado (SI) e por déficit controlado (RDI). O delineamento experimental adotado foi o de blocos casualizados com 4 repetições de 9 tratamentos de irrigação, sendo 4 referentes a SI (T1 - 125%, T2 - 100%, T3 - 75%, T4 - 50%) e 5 caracterizando a RDI [T5 (75% nas fases I e IV e 100% nas fases II e III);T6 (50% na fase I, 100% na fase II e 75% nas fases III e IV); T7 (100% na fase I, 75% nas fases II e III e 50% na fase IV); T8 (50% na fase II e 100% nas demais); e T9 (75% na fase I, 100% na fase III e 50% nas fases III e IV)]. Os índices térmicos ($\Delta T_{dossel-ar}$, CWSI e IG) foram calculados a partir de imagens termográficas capturadas às 8:00h, 12:00h e 16:00h. Os índices térmicos apresentaram altas correlações ($R^2 > 0,7$) entre si em todos os horários avaliados.No contexto de manejo de irrigação os índices térmicos avaliados podem ser utilizados para a pergunta básica de "quando irrigar?", com o $\Delta T_{dossel-ar}$ sendo o mais prático, por não necessitar das temperaturas de referência T_{dry} e T_{wet}.

Palavras-chave: *cucumis melo L.*, Termografia infravermelha,"Quando irrigar?", estresse hídrico.

INTRODUCTION

The need to define appropriate management corroborates the adoption of deficit irrigation techniques in semi-arid regions, not only in terms of the intensity of the deficit, but also in terms of more practical and viable ways of applying and monitoring water stress.

The use of different irrigation strategies reinforces the need for producers to adapt to climatic variations, especially in the semi-arid region, where the water balance is negative. The use of sustained irrigation (SI), such as a fixed water deficiency throughout the crop cycle, has been plausible, but production tends to be lower on average than full irrigation (100% of crop evapotranspiration - ETc). The regulated deficit irrigation (RDI) strategy, according to Mitchell et al. (1984), has the principle of reducing irrigation in phenological periods when the water deficit does not considerably affect the production and quality of the harvest, fully supplying the water needs during the most sensitive phases of the crop cycle.

Despite all the support for monitoring water stress applied to plants, plant-based indicators are used less frequently because they are more complex in collecting information, as well as being an expensive method whose instruments require sophisticated calibrations (Marouelli et al., 2011; Camoglu, 2013). However, leaf temperature has been used because it is simpler to collect and has similar potential to other physiological indicators in terms of the plant's water status, as well as being a non-invasive method, like water potential and gas exchange. Works such as Pipatsitee et al. (2018), Gonzalez-Dugo et al. (2014), García-Tejero et al. (2018) and Gutiérrez-Gordillo et al. (2020) present results that corroborate the monitoring of plant water status via temperature, using thermal images. Aragão et al. (2023) presented results for the melon crop.

Although studies on leaf temperature have been carried out since the 1960s, and the resulting thermal indices express the expected results according to their purposes, there is still no consensus on the most appropriate one. The ΔTcanopy-air is the most practical, while the CWSI (crop water stress index) is considered the most robust. The IG (stomatal conductance index) is presented as proportional to stomatal conductance, and was developed due to the limitations of the CWSI. More detailed considerations are presented in Costa (2023) and Maes and Steppe (2012)

Therefore, the aim of this study was to present correlations between these thermal indices in the response of the flowering and fruiting phase (phase III) of yellow melons (Goldex F1 hybrid) subjected to sustained deficit irrigation (SI) and controlled deficit irrigation (RDI).

MATERIAL AND METHODS

The experiment was characterized by two crop cycles, conducted in the municipality of Sobral, Ceará (3° 42' 40" S; 40° 28' 55" O; altitude 220 m). Belonging to the Brazilian semi-arid region, the predominant climate in the municipality is the "Aw" type, according to the Köppen classification, with average rainfall (1961 - 2016) of 896.7 mm, concentrated between January and May, with maximum temperatures ranging from 37.7°C in October to 29.4°C in May, and minimum temperatures ranging from 24.7°C in December to 18.5°C in July, with average relative humidity of 70% and average annual sunshine of 2,648 h, (INMET, 2018).

Collected at a depth of 0.0 m - 0.2 m, the soil from the experimental area was analyzed at the Soil Laboratory of the IFCE Sobral campus. The results obtained were as follows: pH = 6.2; organic matter (MO) = 0.83 dag/kg; phosphorus (P) = 1.32 mg/kg; potassium (K) = 0.23 cmolc/kg; cation exchange capacity (CTC) = 5.23 cmolc/kg; electrical conductivity of the saturation extract (CEes) = 0.33 dS/m; clay = 56.65 g/kg; silt = 151.79 g/kg; sand = 791.56 g/kg; soil density = 1.32

g/cm3; total porosity = 47%; textural classification = sandy loam. Therefore, according to the recommendations of Crisóstomo et al. (2002), 225.6 kg ha-1 of urea was used to supply N; 400 kg ha-1 of potassium chloride (KCl) was used to supply K2O; and 800 kg ha-1 of simple superphosphate (applied in the foundation)

and 184.6 kg ha-1 of monoammonium phosphate (MAP) was used for fertigation. The value obtained for urea has already been subtracted from the amount of N supplied by MAP. The experimental design adopted was randomized blocks with 4 replications of 9 treatments referring to the replacement of crop evapotranspiration (ETc), defined in Table 2

Table 1 - Definition of sustained irrigation (SI) and regulated deficit irrigation (RDI) treatments as a function of crop evapotranspiration (% of ETc), for the different phenological stages of the melon tree.

| Phenologicalphases | Kc[1] | DAT | Irrigationtreatments (% da ETc) | | | | | | | | |
| | | | SI | | | | RDI | | | | |
			T1	T2	T3	T4	T5	T6	T7	T8	T9
Initial (I)	0,5	0-22	125	100	75	50	75	50	100	100	75
Growth (II)	0,5–1,05	23-40	125	100	75	50	100	100	75	50	100
Floweringandfructification (III)	1,05	41-58	125	100	75	50	100	75	75	100	50
Ripening (IV)	0,75	59-66	125	100	75	50	75	75	50	100	50

Fonte: [1]Allen *et al.* (1998); Kc – coefficient of cultivation; DAT – Days after transplant.

The irrigation method adopted was localized (drip), consisting of a 1" PN 40 main line and 1/2" PN 30 lateral lines with 2.0 L h-¹ self-compensating emitters (maximum pressure 150 kPa), pressurized by an electric pump with a power of 3/4 hp. The distribution uniformity coefficient (CUD) obtained was 97%.

Irrigation was managed via the Class "A" tank (Allen et al., 1998), with daily estimated replacements. The value of the tank coefficient (Kp) was 0.75, which was kept fixed throughout the entire period because local wind speed data was not available. The location coefficient (Kr) was calculated according to Freeman and Garzoli (Vermeirem and Jobling, 1997). Once the values for the daily ETc had been calculated, the replacement needs of the irrigation blades were quantified on a time scale, obtained using the software "Sistema Ômega de Manejo da Microirrigação" (Omega Microirrigation Management System) (Valnir Júnior et al., 2017), with information on the crop, irrigation system and replacement intensity previously entered.

The thermal indices were obtained during the flowering and fructification phase (Phase III) of the melon crop - at 45 DAT in Cycle I and 42 DAT in Cycle II, respectively - and calculated as shown below (García-Tejero et al., 2016):

$$\Delta T_{dossel-ar} = T_C - T_{ar} \qquad (01)$$

$$CWSI = \frac{(T_C - T_{wet})}{(T_{dry} - T_{wet})} \qquad (02)$$

$$IG = \frac{(T_{dry} - T_C)}{(T_C - T_{wet})} \qquad (03)$$

Where: $\Delta T_{canopy-air}$ - temperature difference between the plant and the air; CWSI - crop water stress index; IG - stomatal conductance index; Tc - average plant canopy temperature; Tar - air temperature; T_{dry} - dry reference temperature and T_{wet} - wet reference temperature, respectively simulating leaves with fully closed and fully open stomata.

Thermal images were captured at 8:00 a.m., 12:00 p.m. and 4:00 p.m. using a portable thermal camera, model FLIR E5xt, with emissivity (ε) set at 0.95, and a capture

distance of 1.0 m. The ellipse tool in the Flir Thermal Studio Suite software (Starter model) was used to estimate T_c. For each thermographic image obtained (two per treatment), five ellipses were distributed, resulting in 40 points (n = 40) per treatment.

T_{dry} and T_{wet} were obtained in treatment T2, by selecting two healthy leaves fully exposed to sunlight, respectively, applying Vaseline for 20 to 30 minutes, and water for 10 to 15 seconds, on both sides of the leaf, prior to capture (García-Tejero et al., 2016).

RESULTS AND DISCUSSION

Since their introduction to the scientific community, the objective use of thermal indices has shown satisfactory results for different crops and environments. With regard to daily seasonality, the relationship between thermal data and other ways of monitoring water stress - such as water potential, gas exchange and soil moisture - has been variable during the day, with the most stressful times (between 11 am and 2 pm) showing the best relationships, as observed in the proximity of the averages between cycles of the thermal indices obtained here at 12 pm, and in the works by Gonzalez-Dugo et al. (2014), García-Tejero et al. (2018) and Gutiérrez-Gordillo et al. (2020).

Although the thermal indices adequately represent the proposal for monitoring water stress within their particularities, so far it has not been clear which is the most suitable for irrigation scheduling purposes, although Erdem et al. (2005) obtained good results when irrigating watermelon using different levels of the CWSI. According to the authors, when the assessed CWSI value reached the established level, irrigation was carried out up

to field capacity, so they obtained greater water use efficiency by irrigating when the watermelon had a CWSI of 0.6.

In the context of irrigation management and following the results of Erdem et al. (2005), it can be seen that the CWSI was used to answer the basic question of "when to irrigate?", and it is assumed that the same could be done with the IG, since the input data is the same. For the same purpose, $\Delta T_{canopy-air}$ would also be useful, and more practical, as it does not need the reference temperatures T_{dry} and T_{wet}, however, it has the disadvantage of being more influenced by climatic conditions than the CWSI (García-Tejero et al., 2018), therefore, more than the IG as well.

In addition, looking at Figure 1 and Table 2, in the melon tree, for the conditions of this work, both indices could be used as indicators of "when to irrigate?", explained by the correlations above 0.7 with significance less than or equal to 1%. The CWSI correlations as a function of $\Delta T_{canopy-air}$, considered here to be perfect as they showed R2 of 0.99 and 1.0 with significance of less than 0.1%, are justified by the fact that $\Delta T_{canopy-air}$ as a function of daily variation, at a given time of day, can characterize the difference in temperature between the dry and wet references (as an example, the T_c of the treatments with the greatest deficit and surplus replacement, which, as they suggest, can be used as T_{dry} and T_{wet}, respectively). The same can be said when we consider the correlations of the IG as a function of $\Delta T_{canopy-air}$, which although the correlations were not "perfect" as observed in the CWSI, still provided good results, with R2 coefficients greater than 0.7 and significance of less than 1%.
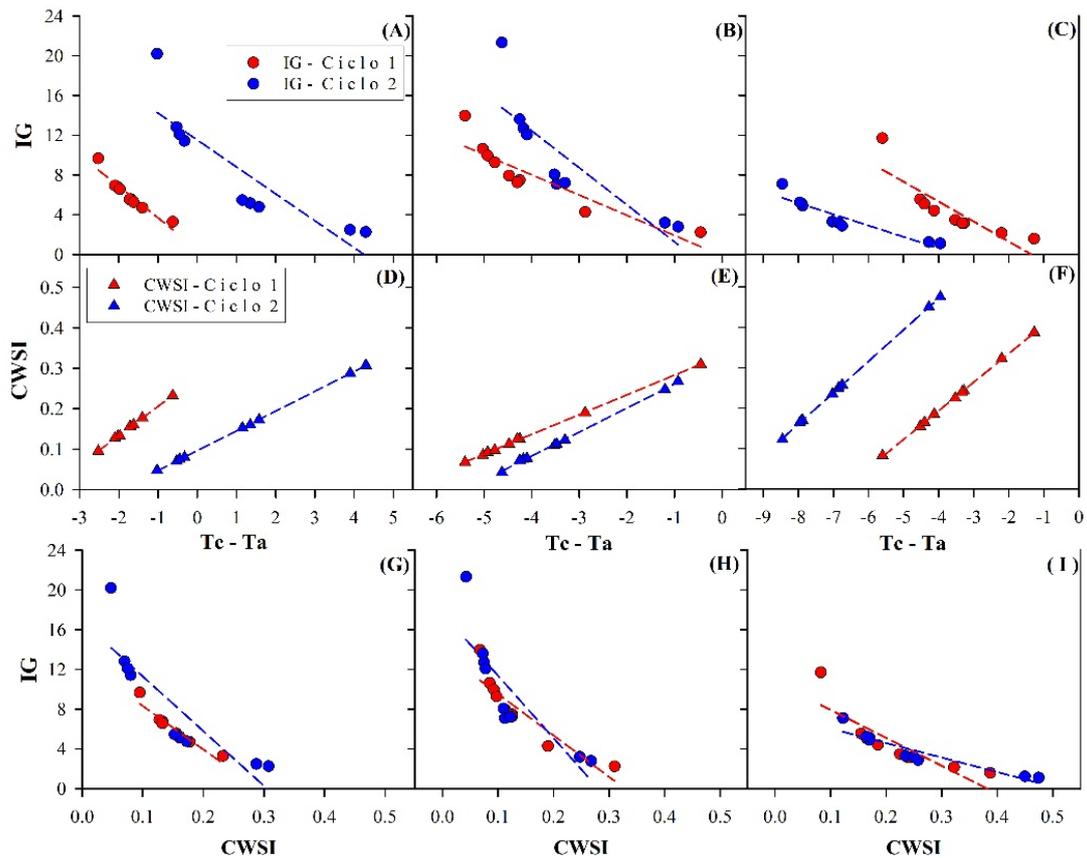
Figure 1 - Correlation between the thermal indices evaluated in two cycles of the melon crop under sustained irrigation (SI) and regulated deficit irrigation (RDI). A, D and G correspond to data obtained at 08 am; B, E and H to data obtained at 12 pm, and C, F and I to data obtained at 4 pm.

Table 2 - Linear regression equations between the thermal indices $\Delta T_{canopy-air}$, CWSI and IG, evaluated in two cycles of the melon crop subjected to sustained irrigation (SI) and regulated deficit irrigation (RDI).

	CYCLEI		
Interaction	**08 am**	**12 pm**	**4 am**
ΔT x CWSI	Y = 0,278 + 0,072x R^2 = 0,99; P < 0,0001	Y = 0,332 + 0,049x R^2 = 1,00; P < 0,0001	Y = 0,476 + 0,071x R^2 = 1,00; P < 0,0001
ΔT x IG	Y = 0,521 – 3,161x R^2 = 0,90; P = 0,0001	Y = - 0,134 – 2,036x R^2 = 0,81; P = 0,001	Y = -2,715 – 2,006x R^2 = 0,75; P = 0,0027
CWSI x IG	Y = 12,684 – 43,755x R^2 = 0,90; P < 0,0001	Y = 13,707 – 41,755x R^2 = 0,81; P = 0,0009	Y = 10,733 – 28,096x R^2 = 0,73; P = 0,003
	CYCLEII		
ΔT x CWSI	Y = 0,096 + 0,049x R^2 = 1,00; P < 0,0001	Y = 0,320 + 0,059x R^2 = 0,99; P < 0,0001	Y = 0,783 + 0,078x R^2 = 1,00; P < 0,0001
ΔT x IG	Y = 11,513 – 2,709x R^2 = 0,77; P = 0,0019	Y = - 2,460 – 3,726x R^2 = 0,73; P = 0,0034	Y = -3,913 – 1,135x R^2 = 0,86; P = 0,0003
CWSI x IG	Y – 16,795 – 55,076x R^2 = 0,76; P = 0,002	Y = 17,654 – 62,845x R^2 = 0,73; P = 0,003	Y = 7,509 – 14,610x R^2 = 0,87; P = 0,0003

When analyzing the relationship between IG and CWSI, it can be seen that the correlation is similar to the relationship between IG and $\Delta T_{canopy-air}$, which was indirectly expected due to the "perfect correlation" between CWSI and $\Delta T_{canopy-air}$. Because they are more robust, in the analysis by Maes and Steppe (2012) it was seen, based on modeling, that both had similar discriminative power, however, the IG can be recommended because it is linearly related to stomatal conductance, whereas the CWSI is better known by scientists.

Despite the differences between thermal indices in terms of robustness, discriminatory power and the influence of environmental variability, future studies should present proposals that make it possible to use infrared thermography and thermal indices commercially.

Possible solutions are: 1) rapid analysis of thermal images and extraction of data for use in the CWSI and IG, which are more complex; 2) a model that makes it possible to estimate the need for irrigation (how much to irrigate?) with practicality, such as a simple measurement of the temperature difference between the canopy and the air ($\Delta T_{canopy-air}$). Similar suggestions were made by Maes and Steppe (2012).

CONCLUSIONS

In the context of irrigation management, the thermal indices evaluated can be used for the basic question of "when to irrigate?", with $\Delta T_{canopy-air}$ being the most practical, as it does not require the reference temperatures T_{dry} and T_{wet}.

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