ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.27, n.6, p.447-456, 2023
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v27n6p447-456

Evaluation of crop water status of melon plants in tropical semi-arid climate using thermal imaging[1]

Imagens térmicas para avaliar o estado hídrico do meloeiro sob clima tropical semiárido

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HIGHLIGHTS:
Deficit irrigation strategies effectively increase water productivity.
Thermal images may be used as an irrigation management strategy.
Mulching is essential for increasing melon fruit yield and water use efficiency.

ABSTRACT: The objective of this study was to analyze the feasibility of using thermal images to estimate the water status of melon plants (*Cucumis melo* L.) in tropical semi-arid climates. The study was conducted in a randomized block design with a split-plot arrangement. The plots comprised of soil cover (with and without mulching), and subplots were constructed using five irrigation regimes (120, 100, 80, 60, and 40% crop evapotranspiration), with five replicates. The following variables were evaluated: canopy temperature (T_{canopy}), leaf water potential, air temperature (T_{air}), soil moisture, crop yield, and thermal index (ΔT), which is defined as the difference between T_{canopy} and T_{air}. ΔT exhibited high correlations with crop yield and water consumption, indicating that thermography is an efficient tool for identifying the water status of melon plants, which could be employed for proper irrigation scheduling under tropical semi-arid scenarios. Moreover, thermal images identified the beneficial effects of soil cover on leaf water status and crop yield, primarily under moderate deficit irrigation. These results demonstrate that mulching is essential for increasing melon yield and water productivity in tropical regions.

Key words: *Cucumis melo*, dryland agriculture, irrigation management, leaf temperature, water stress

RESUMO: O objetivo principal deste trabalho foi avaliar o uso de imagens térmicas para estimar o estado hídrico de plantas de meloeiro (*Cucumis melo* L.) sob clima tropical semiárido. O estudo foi realizado em delineamento de blocos casualizados, em esquema de parcelas subdivididas. As parcelas foram compostas pela cobertura do solo (com e sem cobertura morta) e as subparcelas por cinco regimes de irrigação (120, 100, 80, 60 e 40% da evapotranspiração da cultura - ETc), com cinco repetições. Foram avaliadas as seguintes variáveis: temperatura do dossel (T_{dossel}), potencial hídrico foliar (Ψ_{folha}), temperatura do ar (T_{air}), umidade do solo, produtividade da cultura e índice térmico (ΔT), sendo este definido como a diferença entre T_{dossel} e T_{air}. O ΔT apresentou altas correlações com a produtividade da cultura e o consumo de água da cultura, evidenciando que a termografia é uma ferramenta eficiente para identificar o estado hídrico das plantas de meloeiro e pode ser empregada para uma adequada programação da irrigação em cenários do semiárido tropical. Além disso, o uso de imagens térmicas também permitiu identificar os efeitos benéficos da cobertura do solo sobre o estado hídrico foliar e a produtividade das culturas, principalmente sob moderado déficit de irrigação (DI). Os resultados obtidos também demonstram que a cobertura morta é essencial para aumentar a produtividade do melão e a produtividade da água em regiões tropicais.

Palavras-chave: *Cucumis melo*, agricultura de sequeiro, manejo de irrigação, temperatura foliar, estresse hídrico

• Ref. 266213 – Received 21 Jul, 2022
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• Accepted 27 Dec, 2022 • Published 11 Feb, 2023
Editors: Ítalo Herbet Lucena Cavalcante & Hans Raj Gheyi

Introduction

Globally, melon (*Cucumis melo* L.) is one of the most appreciated fruits by consumers. In Brazil, melon production is concentrated in the northeast region, primarily in the states of Ceará and Rio Grande do Norte, which accounts for over 95% of national production. The primary melon-producing regions have semi-arid characteristics, thereby providing the best climatic conditions. However, they are prone to droughts, and water shortages are a critical issue for sustainable agriculture. Thus, new management strategies are needed for improving irrigation water productivity to support continued production (Cymes et al., 2022).

Deficit irrigation (DI) strategies save water without significantly affecting crop yields (Jahan & Nassiri-Mahallati, 2022). However, effective monitoring of water status in plants during their cultivation cycle is crucial (Poblete-Echeverría et al., 2016; Carrasco-Benavides et al., 2020b). This measurement has been successfully performed using thermal images, which can indicate and detect the effects of water stress in crops (Carrasco-Benavides et al., 2020a; Silveira et al., 2020).

Thermography is a potential tool for estimating canopy temperature (T_{canopy}), which can be used as an indicator of water stress (Costa et al., 2020; Gomes et al., 2021). When combined with automated image analysis, it becomes highly accurate and can measure the relative temperature instead of the real temperature. New devices with high precision and low cost have increased the possibility of using this technique (García-Tejero et al., 2018). Imaging techniques using infrared thermography can detect minimal changes in temperature and are widely used in agriculture (Ali et al., 2022).

With an increase in melon cultivated areas, global growth rates related to water demand have challenged researchers and producers, who seek to increase the efficiency of water use, reduce losses, and more importantly, increase the productivity of vegetable crops (Jacobi & Grandisoli, 2017). The objective of this study was to analyze the feasibility of using thermal images to estimate the water status of melon plants (*Cucumis melo* L.) in a tropical semi-arid climate.

Material and Methods

The experiment was conducted between July and September 2018 in the city of Sobral (03° 41' 10" S, 40° 20' 59" W, altitude 69 m), Ceará, Brazil. The local climate is BSw'h', hot, and semi-arid based on the Köppen classification, with annual sunlight, a mean air temperature (T_{air}), and relative air humidity of 2,563 h, 28.3 °C, and 68%, respectively. The dry season lasts 7–8 months, and the rainy season is concentrated between January to May, with an average annual rainfall of 854 mm (INMET, 2018). The soil in the area is classified as Entisol (United States, 2014). The physicochemical characteristics of the soil samples collected at 0–0.20 m depths of soil layer are shown in Table 1.

Seeds of yellow melon hybrid Goldex F1 were sown in polystyrene trays, with 128 cells each, using cattle manure and washed sand at 1:1 ratio as the substrate (v/v). After emergence, the seedlings were kept for approximately 7 days in the trays, a period needed for the development of two true leaves, and then transplanted to the field.

Table 1. Chemical and physical characteristics of topsoil (0-0.20 m) of the experimental area

Parameters	Values
Chemical	
OM	28.46 g kg^{-1}
Mg	1.80 cmol$_c$ dm^{-3}
K	1.62 cmol$_c$ dm^{-3}
P	174 mg dm^{-3}
pH	8.3
Al	0.0
EC_{SE}	1.02 dS m^{-1}
Physical	
Coarse sand	384 g kg^{-1}
Fine sand	505 g kg^{-1}
Silt	78 g kg^{-1}
Clay	33 g kg^{-1}
Natural clay	29 g kg^{-1}
Soil density	1.44 kg dm^{-3}
Particle density	2.65 kg dm^{-3}

OM- organic matter; Mg- magnesium; K- potassium; P- phosphorus; pH- soil pH; Al- aluminum; and EC_{SE}- electrical conductivity of the soil saturation extract

A randomized complete block design (with a split-plot arrangement) was used with five replicates per irrigation regime (IR). The plots comprised of soil cover (with and without plant material mulching), and subplots were formed using five IRs. The planting spacing was 2.0 × 0.5 m, and each subplot had 10 plants. Mulching was performed with dry leaves of carnauba [*Copernicia prunifera* (Miller) H. E. Moore] residue by keeping a 3.0 cm layer around the melon plants. This is a by-product of carnauba wax, which is extremely abundant in the region. Silva et al. (2014) reported the following chemical composition of this leaf residue: N = 27.13 g kg^{-1}, P = 1.46 g kg^{-1}, K = 5.41 g kg^{-1}, Ca = 4.98 g kg^{-1}, Mg = 2.88 g kg^{-1}, Na = 1.4 g kg^{-1}, B = 50.54 mg kg^{-1}, Fe = 47.78 mg kg^{-1}, Cu = 0.59 mg kg^{-1}, Mn = 2.07 mg kg^{-1}, and Zn = 0.56 mg kg^{-1}. The five IRs were defined as a percentage of crop evapotranspiration (ET_C) as follows: (IR_1, 120%; IR_2, 100%; IR_3, 80%; IR_4, 60%; and IR_5, 40% ET_C). The IRs were defined through the inclusion of water deficits that would not kill the plants and were maintained at higher than 100% to ensure adjustments of the crop coefficient (K_c) for the region. Spraying of pesticides (Mancozeb, Cyromazine, and Acetamiprid) registered with the Ministério da Agricultura, Pecuária e Abastecimento was performed to control pests and diseases.

The nutritional requirements of the crops were 140 kg ha^{-1} N, 300 kg ha^{-1} K_2O, and 240 kg ha^{-1} P_2O_5. The N, K, and P sources used were urea, potassium chloride, and triple superphosphate, respectively. Top dressing was performed via daily fertigation using the Venturi system. A drip irrigation system was employed with PCJ–CNL self-compensating in-line button drippers at a mean pressure and nominal flow of 150 kPa and 4.2 L h^{-1}, respectively, with one dripper per plant. Drippers were previously evaluated under laboratory conditions using Christiansen's and distribution uniformity coefficients, which presented values of 91% and 84%, respectively.

The daily amount of water applied was determined by the ET_C and estimations by the means of reference evapotranspiration (ET_0) and Ks_c (Allen et al., 1998). The ET_0 was estimated by direct readings of daily evaporation in Class

A pan, which was installed next to the experimental area by adopting a tank coefficient of 0.72, according to local climate conditions. The Ks_c used were 0.50, 0.80, 1.05, and 0.75, as recommended by Doorenbos & Pruitt (1977) and Doorenbos & Kassam (1994), corresponding to periods of vegetative growth (35 days), flowering (15 days), and fruit production (10 days) and maturation (7 days), respectively.

The soil cover factor for localized irrigation was calculated using a ruler to measure the dimensions of the melon plant branches in the cross section of the planting rows by dividing the value of the row spacing. The amount of water applied in each irrigation treatment throughout the plant cycle was 386.69, 322.24, 257.79, 193.34, and 128.89 mm, for IR_1, IR_2, IR_3, IR_4, and IR_5, respectively.

Soil moisture was determined in samples collected at 0–0.20 m soil layer at 15, 30, 45, and 60 days after transplanting (DAT). Soil moisture (g g^{-1}) was determined in three replicates for each treatment using the gravimetric method (Jarrell et al., 1999).

Leaf water potential (Ψ_{leaf}) was measured at 15, 30, 45, and 60 DAT at 5:00 a.m., according to Scholander et al. (1965), using a pressure camera (Model 3115, Soil Moisture). The third leaf, counted from the apex of the stem (i.e., the youngest mature leaf), was chosen for the measurement. Three replicates were used for each treatment.

T_{canopy} was measured using an FLIR I40 thermal camera on the same dates at which the soil moisture and Ψ_{leaf} were measured. Thus, on days when the Ψ_{leaf} and soil moisture were evaluated, the T_{canopy} of the melon crop was also measured. The device instantaneously identifies temperature with a thermal sensitivity of 0.06 °C (thermal image resolution: 80 × 60; multispectral image resolution: 320 × 240). Thermal images were captured at distances between 0.50 and 1.0 m from the plants. Images were acquired manually using a camera on a tripod for better image adjustment. All images were captured between 8:00 and 9:00 a.m. (Brazilian Time; GMT-3) and treated using FLIR QuickReport software.

To quantify the average T_{canopy}, three images of each plant were captured from three plants per treatment. T_{air} was monitored using a HOBO U12-012 thermohygrometer, with a data logger installed next to the experimental area. T_{canopy} and T_{air} data were used to calculate the thermal index (ΔT; T_{canopy} - T_{air}) according to Jackson et al. (1981).

Fruit yield was determined for each experimental unit by extrapolating the values in t ha^{-1}. Only fruits with commercial characteristics (Campelo et al., 2014) were counted, and all fruits with defects were eliminated. The fruits were sorted and classified manually at 55 DAT, when all fruits had a yellow color and characteristics suitable for commercialization.

The data were subjected to analysis of variance (F-test), Tukey's test ($p \leq 0.05$), and regression analysis. The models were chosen based on the significance of the regression coefficients using the F-test ($p \leq 0.05$) and the highest value of the coefficient of determination.

Results and Discussion

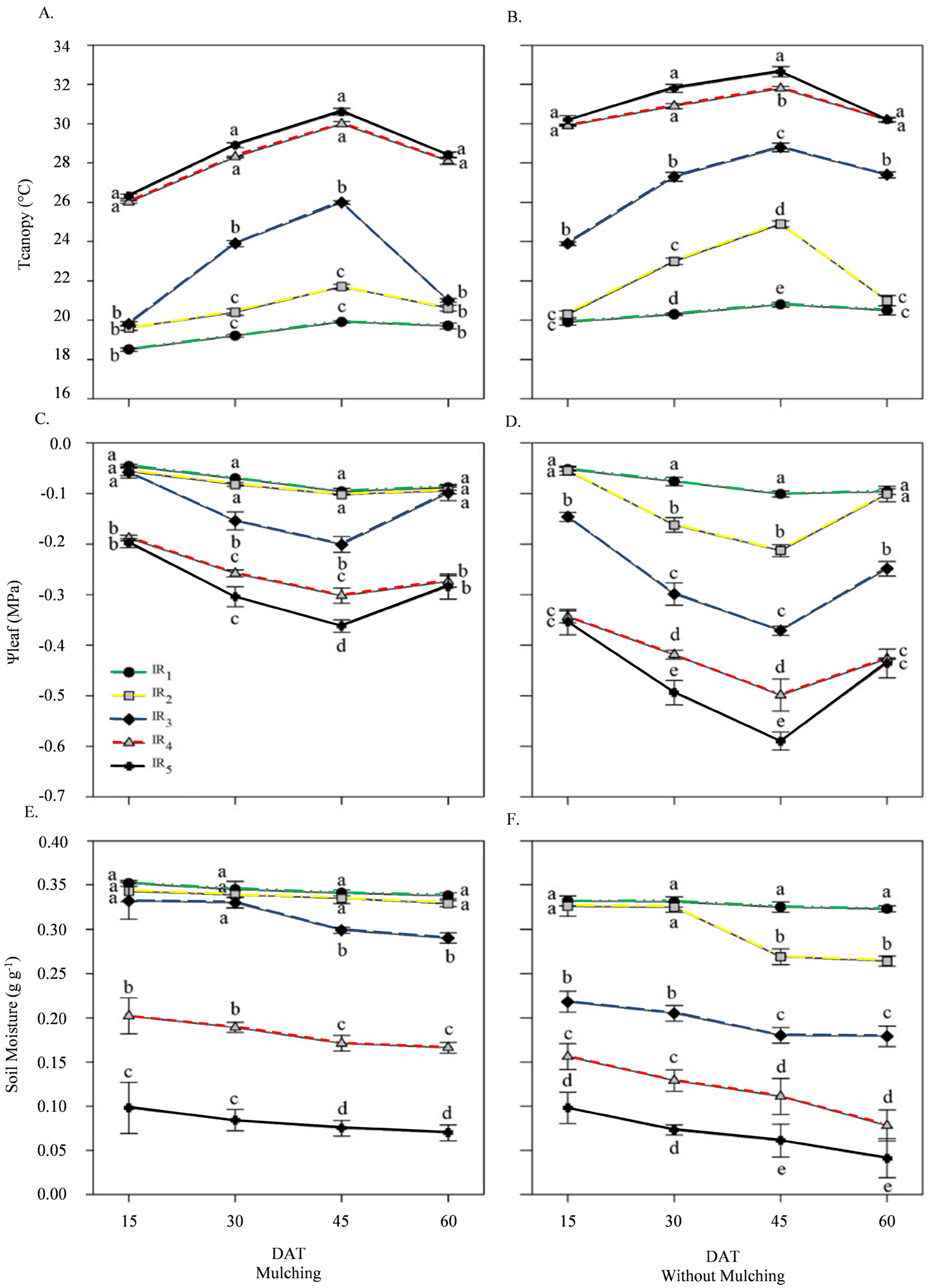
Figure 1 shows the mean values of T_{canopy}, Ψ_{leaf}, and soil moisture measured at 15, 30, 45, and 60 DAT in the soil with and without mulching. Figures 1A and B exhibit an increase in T_{canopy} up to 45 DAT, followed by a decrease, except in the treatments with 120% ET_c. Because the water consumption in melon plant progressively increases over its phenological cycle, it is likely that most IRs did not meet the water requirements of the crop, particularly during the period of greatest demand. This assumption is based on the increases in T_{canopy}, which usually occur when soil water availability is low and stomatal conductance decreases. According to Dejonge et al. (2015), T_{canopy} increases when solar radiation is absorbed; however, the plant is cooled when this energy is used for leaf transpiration.

In general, T_{canopy} decreased when water availability was elevated. When the plant was under well-watered conditions, T_{canopy} remained between 18 and 20 °C, with small changes throughout the crop cycle (Figures1A and B). These results are similar to those obtained for other crops, such as vineyards and olive orchards (Poblete-Echeverría et al., 2016), where water status was estimated in plants using thermal information. Similarly, other studies have reported significant correlations between thermal information and physiological variables related to plant water status (Ramírez-Cuesta et al., 2022).

In general, higher T_{canopy} values were observed in IR_4 and IR_5 treatments. This could be related to the greater water restriction imposed by these treatments during the melon crop cycle. Under these conditions, the plant closed its stomata and reduced transpiration, which increased the T_{canopy}. García-Tejero et al. (2018) and Pou et al. (2014) conducted studies on almonds and grapevines, respectively, using thermography and observed that plants subjected to water restriction conditions had higher T_{canopy}. However, variations in meteorological variables can also directly influence the T_{canopy} data (Javadian et al., 2022).

Plants growing in soil without mulching exhibited mean T_{canopy} values of 1.3–3.6 °C, which were higher than those observed in the treatments with soil cover. It is likely that mulching led to lower evaporation, and consequently, a higher amount of water remained available to plants. The use of mulch resulted in soil water conservation (Figures 1E and F), as demonstrated in other studies (El-Beltagi et al., 2022), helping plants maintain a lower T_{canopy} (Ni et al., 2019). Moreover, this technique contributes to increased crop yields and water use efficiency, as demonstrated in a study conducted in the semi-arid regions of China (Wang et al., 2016).

The mean values of Ψ_{leaf} in IR_1 and IR_2 were -0.079 and -0.090 MPa, respectively, indicating that the water supply was adequate in these treatments, with plants exhibiting a good water status in the leaves. However, Ψ_{leaf} decreased in IR_3, IR_4, and IR_5, especially at 45 DAT (Figures 1C and D), which is the most critical stage in the melon crop cycle, with flowering and early fruit production. These results indicated that the water deficit intensified during this period, mostly in treatments without mulching, which also exhibited lower soil moisture (Figures 1E and F). According to García-Tejero et al. (2016), Ψ_{leaf} is a good indicator of leaf water status. It is particularly important to indicate the variations and water stress levels of plants under poor irrigation or different soil management (for example, soil cover), as shown in this study (Figure 1).

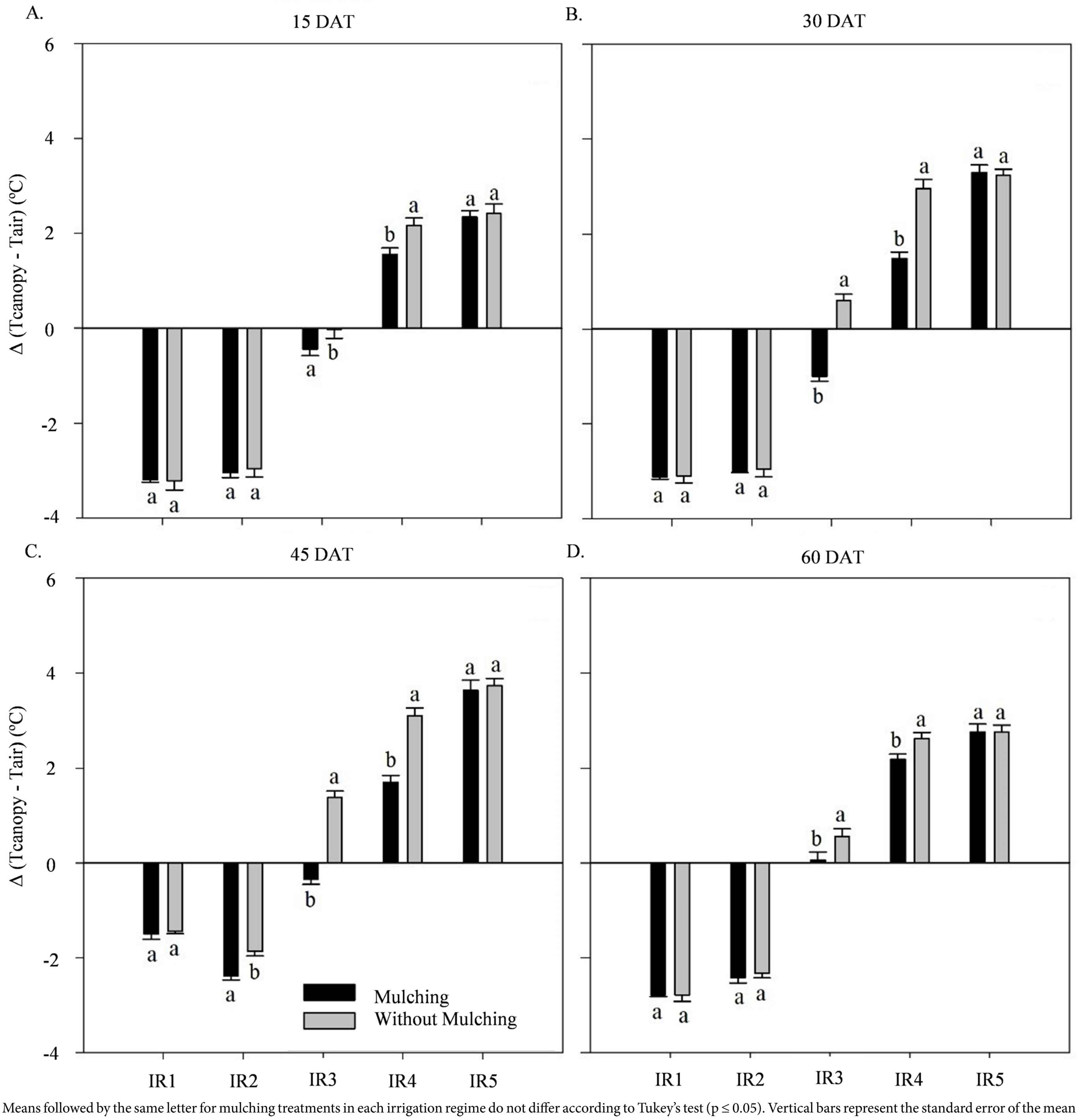


Means followed by the same letter for irrigation treatments at each measurement date do not differ according to Tukey's test ($p \leq 0.05$). Vertical bars represent the standard error of the mean

Figure 1. Variations in mean canopy temperature (T_{canopy}) (A and B), leaf water potential (Ψ_{leaf}) (C and D), and soil moisture (E and F) at 15, 30, 45, and 60 days after transplanting (DAT) of melons under different irrigation regimes (IR_1- 120%, IR_2- 100%, IR_3- 80%, IR_4- 60%, and IR_5- 40% ET_c) in soil with (A, C, and E) and without mulching (B, D, and F)

ΔT was not affected by soil cover in the treatment with the highest DI (60% less water; IR_5) in all evaluations (Figure 2). This treatment also demonstrated the highest and most positive values of ΔT, indicating considerable effects on the leaf water status. In contrast, the soil cover results were identical in the treatments with high irrigation depths (IR_1 and IR_2) at 15, 30, and 60 DAT, but the values were always negative, suggesting improvements in crop water status (Figures 2A, B, and D). However, the best contributions of mulching were observed in treatments with moderate DI (up to 40% less water; IR_3 and IR_4), when plants exhibited lower thermal indices at all evaluations compared with the values observed in plants grown in soil without mulching. Thus, soil cover is efficient in maintaining soil moisture values for a longer period, which reduces the risk of water stress in crops (Wang et al., 2016). Our results demonstrated the importance of mulching to ensure soil water availability at the time of highest demand, even with high irrigation depths (100%), and for treatments with moderate DI (primarily up to 20%), helping plants maintain the leaf water status, as shown by thermal images and Ψ_{leaf} analyses (Figure 1).

ΔT (T_{canopy} - T_{air}) is recommended to estimate crop water stress using thermometric images because of its feasibility (García-Tejero et al., 2018). Urban et al. (2017) reported temperature differences up to 9 °C between plants grown in dry and moist



Means followed by the same letter for mulching treatments in each irrigation regime do not differ according to Tukey's test (p ≤ 0.05). Vertical bars represent the standard error of the mean

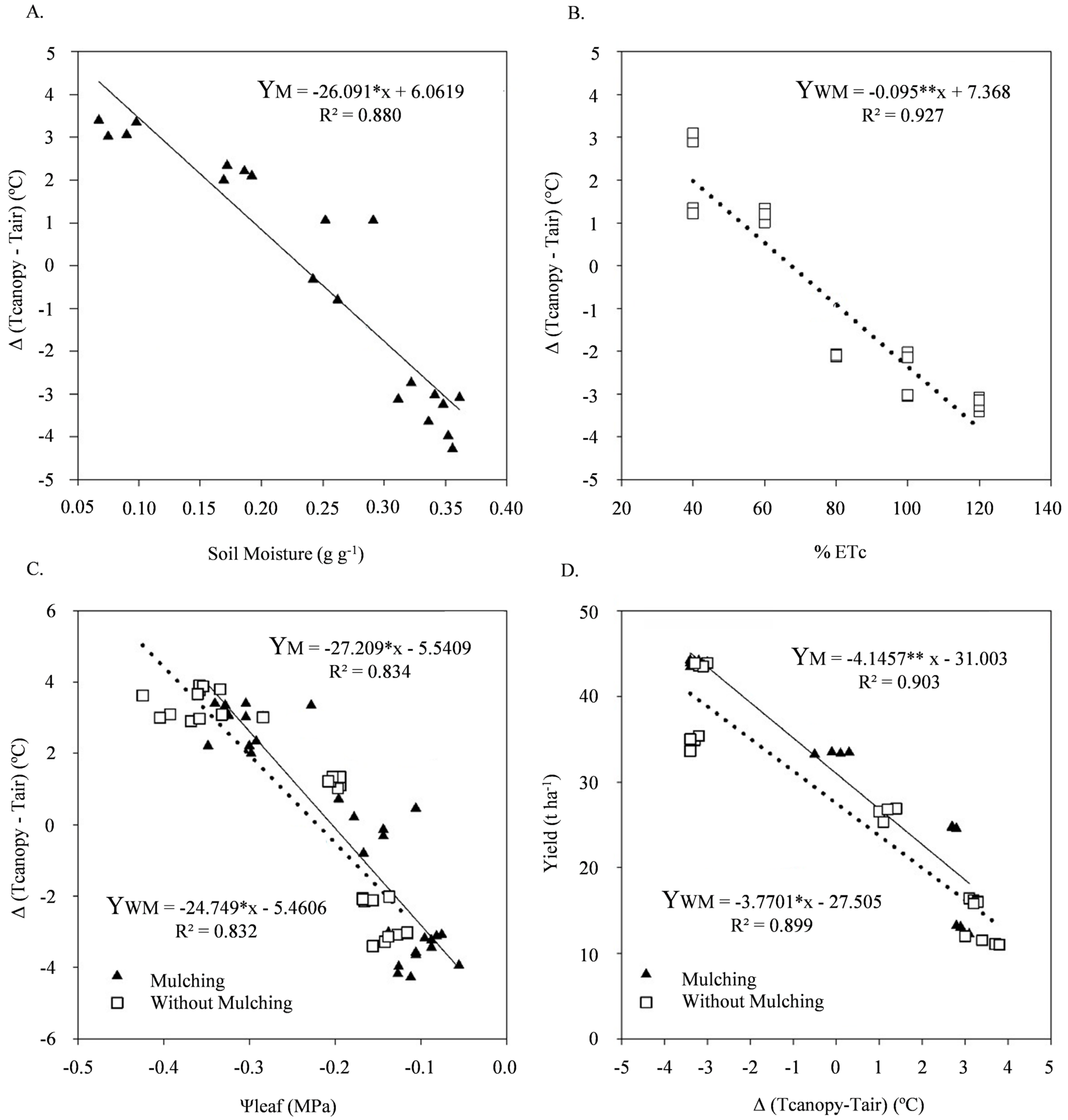
Figure 2. Means of thermal index (ΔT; T_{canopy} - T_{air}) as a function of irrigation regimes (IRs) and soil cover (with and without of mulching) at 15 (A), 30 (B), 45 (C), and 60 (D) days after transplanting (DAT) of melons at different IRs (IR_1 - 120%, IR_2 - 100%, IR_3 - 80%, IR_4 - 60%, and IR_5 - 40% ET_c)

soils. Our results also indicated significant differences in ΔT between IR treatments and between treatments with and without soil cover (Figure 2). Furthermore, the use of mulching caused better plant development conditions and increased water use efficiency through lower water loss by evaporation, leading to a greater water storage volume for longer periods (Li et al., 2013).

ΔT was negatively correlated with soil moisture (Figure 3A) and ET_C (Figure 3B). This implies that under ideal soil moisture conditions, there are high transpiration rates in the whole plant, markedly increasing and reducing T_{canopy}. In contrast, low soil moisture not only affects plant water relations by reducing leaf water content and cell turgor but also affects stomatal conductance, leaf transpiration, T_{canopy}, and carbon assimilation rates.

Figure 3C illustrates the variations in ΔT (T_{canopy} - T_{air}) as a function of Ψ_{leaf}, which exhibits a downward linear trend. Positive ΔT values occurred at lower Ψ_{leaf}, implying that water restriction made the T_{canopy} higher than the T_{air}. These results indicated that under these conditions, melon leaves presented lower transpiration rates and consequently, T_{canopy} increased, implying that the crop is experiencing water stress. Similar results were reported by Mira-García et al. (2022).

Figure 3D demonstrates that when ΔT was approximately -3.2 °C, crop yield reached values of approximately 44.0 t ha^{-1}.



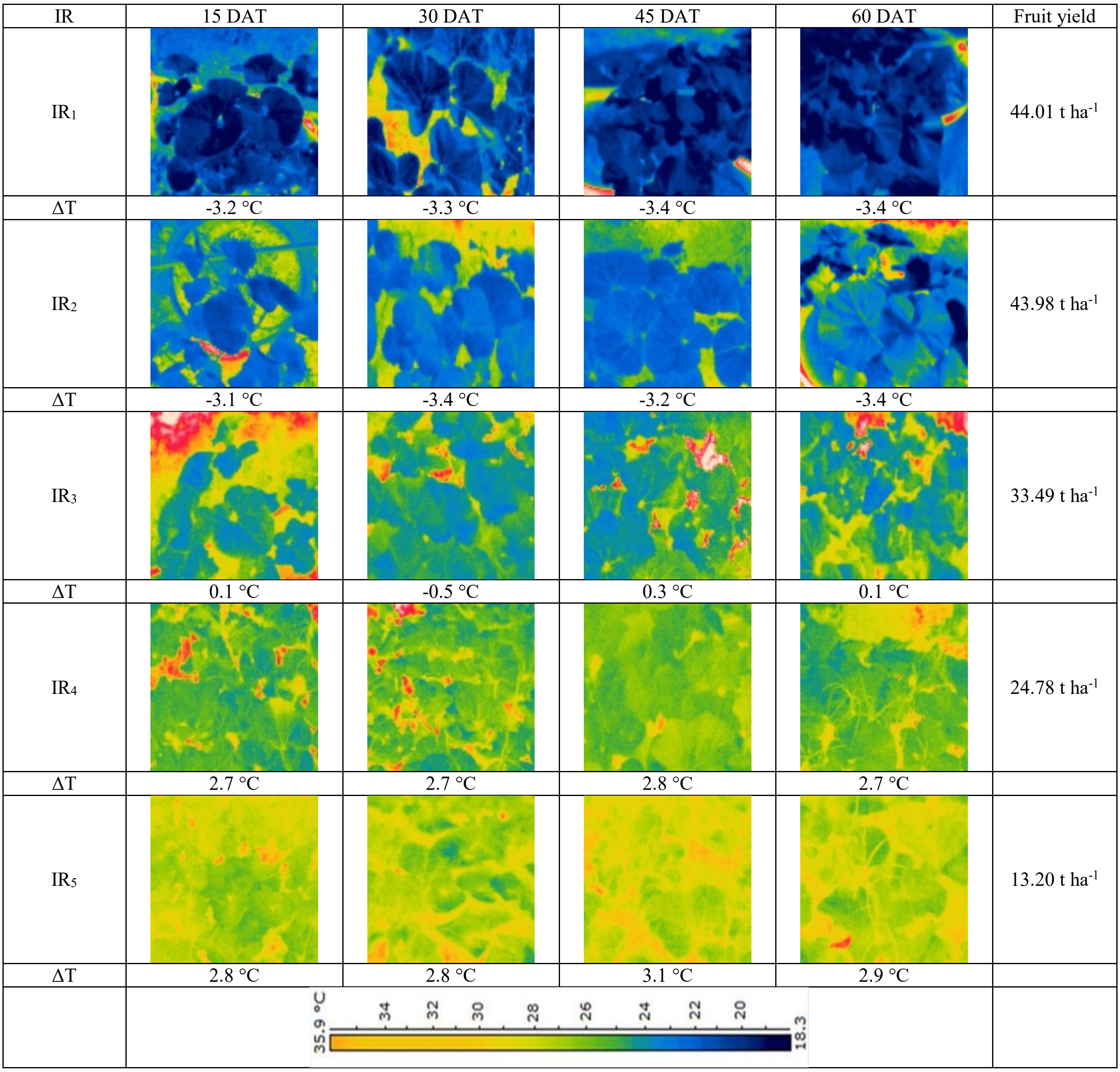
* Significant at $p \leq 0.05$; and ** Significant at $p \leq 0.01$ according to F test; M - Mulching; WM - without mulching

Figure 3. Relationships between thermal index (ΔT; T_{canopy}-T_{air}) and soil moisture (A), ΔT and crop evapotranspiration (ET_c) (B), ΔT and leaf water potential (Ψ_{leaf}) (C), and fruit yield and ΔT (D) of melons, as a function of soil cover

However, when ΔT (T_{canopy} - T_{air}) was approximately 0.0 °C, fruit yield decreased to 34.0 t ha^{-1}. On comparing obtained crop yields with the highest and lowest ΔT (T_{canopy} - T_{air}) values, a difference of 30.47 t ha^{-1} was observed, corresponding to 69% production loss. That is, when the thermal indices were higher, melon fruit yield decreased significantly. The reduction in fruit yield under high T_{canopy} supports the findings of Dejonge et al. (2015), who discussed the results obtained in their study with maize.

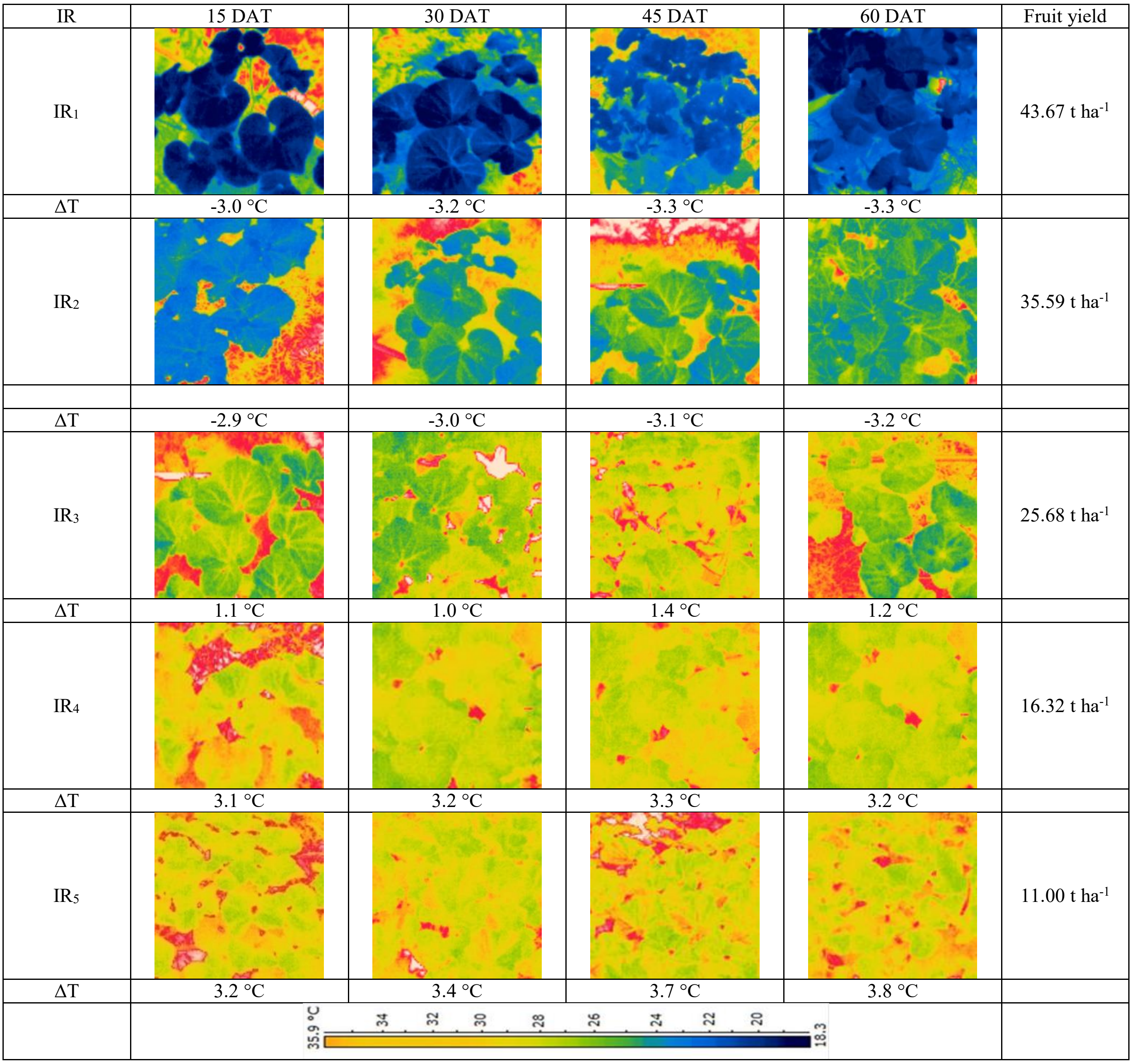
The thermal images presented in Figures 4 and 5 show the impact of the treatments on ΔT and melon yield. In the mulching treatment (Figure 4), images of plants under no DI (IR_1 and IR_2) presented values lower than -3.3 °C, with a yield of 44.0 t ha^{-1}. In contrast, ΔT was higher in all observations for plants under low irrigation depths (IR_4 and IR_5), and the yield reached only 24.78 and 13.20 t ha^{-1}, respectively. These results exhibited that the use of infrared thermal images aided in recognizing the differences in the water availability for full and DI treatments, as was also demonstrated for vineyards and olive orchards (Poblete-Echeverría et al., 2016; García-Tejero et al., 2018).

In contrast, in treatments without mulching (Figure 5), ΔT ranged from -3.0 °C under full irrigation to +3.8 °C for the most stressed treatment. On comparing the data in Figures 4 and 5, it can be observed that plants cultivated in the soil with mulch exhibited better physiological performance and higher production. Ni et al. (2019) stated that the use of soil cover results in lower T_{canopy} and favors the assimilation of nutrients, root development, water retention, and soil aeration.



DAT- days after transplanting

Figure 4. Thermal images, thermal index (ΔT), and fruit yield of melons under different irrigation regimes (IR; IR_1-120, IR_2-100, IR_3-80, IR_4-60, and IR_5-40% ETc) grown in soil with mulching. The values of ΔT (T_{canopy} - T_{air}) correspond to the average of nine measurements taken for each treatment at each date of evaluation



DAT- days after transplanting

Figure 5. Thermal images, thermal index (ΔT), and fruit yield of melons under different irrigation regimes (IR; IR_1-120, IR_2-100, IR_3-80, IR_4-60, and IR_5-40% ETc) grown in soil without mulching. The values of ΔT (T_{canopy} - T_{air}) correspond to the average of nine measurements taken for each treatment at each date of evaluation

Our results indicated that the analysis of thermometric images accurately demonstrated the positive impact of this technique, exhibiting clear differences between treatments with and without soil cover. These beneficial effects of soil cover, confirmed by thermal images, have been reported by other authors (García-Tejero et al., 2016).

Our results exhibited that mulching was efficient in reducing ΔT and increasing fruit yield, especially in treatments with moderate water stress. For treatments with 20% and 40% DI, there were increases of 30.6% and 52%, respectively, in crop yields of plots with mulching compared with those of without mulching. Moreover, there was a beneficial effect of soil cover in the treatment without water deficit (100% ETc), with approximately 24% increase in crop yield. This treatment may have presented a deficit in the stage of greater water consumption, as evidenced by Ψ_{leaf} and T_{canopy} data, especially in soil without mulching (Figure 1). The use of a nonregional K_c explains, at least in part, the water deficit observed in this treatment. However, the treatment with 120% ET_c application exhibited no differences between the treatments with and without mulching, indicating that additional 20% water was necessary to meet the demand of crop grown without soil cover.

Conclusions

1. Thermal index showed high correlation with crop yield, leaf water potential, and crop water consumption.

2. Thermal images are efficient for identifying the water status of melon plants and may be employed as an irrigation management strategy in tropical semi-arid climates.

3. Thermal images identified the beneficial effects of soil cover on leaf water status and crop yield, especially under moderate deficit irrigation.

4. Mulching is essential for increasing the fruit yield and water use efficiency in melon cultivations in semi-arid tropical regions.

Acknowledgements

The authors acknowledge the "Conselho Nacional de Desenvolvimento Científico e Tecnológico," "Instituto Federal de Educação, Ciência e Tecnologia do Estado do Ceará (*Campus* Sobral)," and "Coordenação de Aperfeiçoamento de Pessoal de Nível Superior," Brazil, for their financial support in this research.

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