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Yield response of seedless watermelon to different drip irrigation strategies under Mediterranean conditions

Abdelsattar Abdelkhalik[ab], Nuria Pascual-Seva[c], Inmaculada Nájera[d], Alfonso Giner[d], Carlos Baixauli[d], Bernardo Pascual[e]*

[a] Departamento Producción Vegetal. Universitat Politècnica de València. Camí de Vera s/n. 46022, Valencia, Spain.

[b] Horticulture Department, Faculty of Agriculture, Fayoum University, 63514, Fayoum, Egypt.

[c] Centro Valenciano de Estudios sobre el Riego. Universitat Politècnica de València. Camí de Vera s/n. 46022, Valencia, Spain.

[d] Centro de Experiencias de Cajamar Paiporta. Camino del Cementerio Nuevo s/n. 46200, Valencia, Spain.

*Corresponding author

ABSTRACT

Water is an essential resource for food production, as agriculture consumes close to 70% of the total freshwater, and its shortage is becoming critical in arid and semiarid areas of the world. Therefore, it is important to use water more efficiently. The objectives of this project are to determine the productive response and the irrigation water use efficiency of seedless watermelon to three irrigation management strategies over two growing seasons. This was done by applying 100, 75 and 50% of the irrigation water requirements (IWR) the first year, in the second year added six additional treatments, of which three treatments were regulated deficit irrigation with 75% IWR during the vegetative growth, fruit development and fruit ripening stages, and the other three treatments were with 50% IWR during the same stages. The exposure of watermelon plants to severe deficit irrigation resulted in a reduction in dry biomass, total and marketable yield, average fruit weight, fruit number and harvest index, and without improvement of marketable fruit quality.

The fruit ripening was the less sensitive stage to water deficits. Relative water content and cell membrane stability index decreased as the water deficit increased. Irrigation water use efficiency decreased to a lesser extend during the fruit ripening stage than when water restriction were applied during different growth stages. If water is readily available, irrigating with 100% of water requirements is recommended, but in the case of water scarcity, applying water shortage during fruit ripening stage would be advisable.

Keywords: Evapotranspiration; irrigation water use efficiency; water status; deficit irrigation; soluble solids; fruit size.

1. Introduction

Watermelon [*Citrullus lanatus* (Thun.) Matsum. and Nakai] is an important crop around the world, with a production approximately 117 million Mg from 3.5 million ha (FAO, 2017). Currently, the leading watermelon-producing countries are China, Turkey and Iran. Spain is the main producer of watermelon for the European community, with 969,327 Mg from 17,360 ha (FAO, 2017).

Irrigation water is an essential element for crop production (Howell, 2001; Steduto et al., 2012). Agriculture uses approximately 70% of freshwater; in Spain, agriculture utilizes approximately 68% of total water use (FAO, 2016)**.** During recent years, freshwater shortage is becoming critical in arid and semiarid areas of the world with increasing competition for water across agricultural, industrial and urban consumers (Chai et al., 2016). Rapid population growth, other human activities and the greater incidence of drought, particularly in the Mediterranean area, are increasing the demand for fresh water (Fereres, 2008). This water scarcity and the incremental increase in irrigation costs have led to heightened interest in improving the productivity of water use in crop production (Bessembinder et al., 2005; Fereres and Soriano 2007; Steduto et al., 2012; Reddy, 2016).

Irrigation water-use efficiency (IWUE) is a common indicator employed to assess the efficiency of the use of irrigation water in crop production (Bos, 1980; Tolk and Howell, 2003; Pascual-Seva et al., 2016). At present, there are challenges in maximizing IWUE and increasing crop productivity per unit of water applied. Within this context, the use of deficit irrigation (DI) strategy is a technique of applying irrigation less than the optimum crop water requirements with a result to improve water use efficiency (Pereira et al., 2002; Costa et al., 2007; Capra et al., 2008; Evans and Sadler, 2008; Chai et al., 2016). The real challenge is to establish DI on the basis of maintaining or even increasing crop productivity while saving irrigation water and, therefore, increasing the IWUE (Chai et al., 2016). For this reason, DI requires precise knowledge of the crop yield response to water applied (Fereres and Soriano, 2007). Currently, DI is a common practice throughout the world, especially in dry regions, where it is more important to maximize crop water productivity rather than the harvest per unit land (Ruiz-Sánchez et al., 2010). Regulated deficit irrigation (RDI) is the treatment of water stress during certain crop developmental periods (Fereres and Soriano, 2007).

Water content and water potential have been used as indicators of leaf water status. The use of water content has been replaced by the relative water content (RWC) which are measurements based on the maximum amount of water a tissue can hold (Yamasaki and Dillenburg, 1999). RWC reflects the metabolic activity in tissues, and it is used as a meaningful index for dehydration tolerance (Anjum et al., 2011; Kalariya et al., 2015). RWC correlates closely with a plant's physiological activities, soil water status (Tanentzap et al., 2015) and is a parameter used for screening the drought tolerance of different genotypes (Tanentzap et al., 2015). On the other hand, the cell membrane stability index (MSI) is also widely used as an indicator of leaf desiccation tolerance (Chai et al, 2010), which detects the degree of cell membrane injury induced by water stress (Bajji et al., 2002).

Watermelon grows in the summer, when evapotranspiration (ET) demands are high and rainfall is scarce, particularly in a Mediterranean-type climate, where irrigation is needed for any significant summer cropping (Turner, 2004). Watermelon is considered to be very sensitive to water stress with larger yield reductions when water use is reduced (Steduto et al., 2012). The timing and extent of water deficit irrigation are important for efficient water use and maximizing yield (Erdem and Nedim Yuksel, 2003; Yang et al., 2017). Currently, there is little available data of DI for seedless watermelon, especially for developed hybrids. Therefore, it is important to identify the best practices for the water management of watermelon using DI techniques. The objective of this study is to evaluate response of watermelon growth, fruit yield, fruit quality, IWUE, and plant water status under DI in open field conditions.

2. Materials and methods

2.1. Experimental site

Field experiments were carried out in two plots at the Cajamar Experimental Center in Paiporta, Valencia, Spain (39.4175 N, 0.4184 W), during the 2016 and 2017 growing seasons. The soils are deep, with a coarse texture (Table 1), and are classified as Anthropic Torrifluvents according to the USDA Soil Taxonomy (Soil Survey Staff 2010). Although the soil of the two plots was apparently similar, soil analyses indicated that the soil in 2017 was sandier than in 2016. In addition, while the soil texture in 2017 was uniform throughout the profile (loam), the soil in 2016 presented a higher percentage of clay (clay loam) at 0.30 m compared to that at a 0.15 m depth. The analyses indicate that the soils have a slightly alkaline pH (on average 7.4), are fertile (1.89% organic matter content; EC 0.39 dS m^{-1}), and present high available phosphorous (43 mg kg^{-1}; Olsen) and potassium (340 mg kg^{-1}; ammonium acetate extract) concentrations. Irrigation water was pumped from a well, with EC 2.53 dS m^{-1} and 77 mg kg^{-1} N-NO^{3-} content.

According to Papadakis's agro-climatic classification (Verheye, 2009), the climate is subtropical Mediterranean (Su, Me) with hot dry summers and an average annual rainfall of approximately 450 mm, irregularly distributed throughout the year, with approximately 40% falling in autumn. Figure 1 shows the most significant climatological data of the growing seasons expressed as average monthly values: temperature (ºC), precipitation (mm), and reference evapotranspiration (ET_o; mm) obtained from a Class A evaporation pan adjacent the experimental plots.

2.2. Plant material and management

Plants of the triploid watermelon cv. *Stellar F1* (Nunhems®) grafted on the hybrid ‘*Shintoza*’ (*Cucurbita maxima* x *Cucurbita moschata*) were transplanted when plants had reached the two-leaf stage in an open field at a spacing of 1.0 m by 3.0 m apart in plastic mulched rows, following traditional practices used in the area**,** on 19 May 2016 and 15 May 2017. Shortly afterwards, plants were de-topped to force the growth of four tertiary vines per plant, as described by López-Galarza et al. (2004). The row length was 10.0 m, and the width of the raised bed covered by the plastic mulch was approximately 0.60 m.

The cv. *Premium*, also grafted on the hybrid ‘*Shintoza*’, was used as a pollinator with a proportion of 33% to ensure a sufficient pollen amount for the pollination of the triploid cv. The incorporation of nutrients (250-100-250 kg ha^{-1} N-P_2O_5-K_2O) was performed by fertigation, following the recommendation described by Pomares et al. (2007). Fruit harvest started on 25 July 2016 and lasted until 1 August 2016 and again on 20 July 2017 until 3 August 2017, with three recollections each year.

2.3. Water requirements and irrigation treatments

From transplanting until establishment (considered as the initial period), the plants of all strategies were irrigated without restrictions. Different irrigation strategies were initiated following this establishment time period. The growth stages are described as follows: (1) initial, from transplanting until establishment; (2) crop development, from establishment until first fruit setting; (3) fruit growth, from first fruit setting until full fruit size; and (4) fruit ripening, from full fruit size until harvest. These stages correspond to FAO crop growth stages for crop evapotranspiration

(ETc) determination (Allen et al., 1998): (1) initial; (2) growth development; (3) mid-season stage; and (4) late-season stage.

Two irrigation experiments were completed. The first experiment was conducted in 2016 and 2017 that included three irrigation rates (IR) corresponding to 100% (T1), 75% (T2) and 50% (T3) of the irrigation water requirement (IWR; mm day^{-1}) throughout the growing season. The second experiment was carried out in 2017 only, with six additional treatments that included T4, T5 and T6 that corresponded to RDI rates with 75% nominal crop water use at crop growth stages 2, 3 and 4 and T7, T8 and T9 with 50% water use at the same crop stages. The IWR was determined using the following equation:

$$\mathrm{IWR} = \frac{\mathrm{ETc} - \mathrm{Pe}}{\mathrm{Ef}}$$

where ETc is the crop evapotranspiration, Ef is the irrigation efficiency including percolation and uniformity) which was considered to be 0.95 (Pomares et al., 2007) and Pe is the effective precipitation (mm), determined from rainfall data using the method of the U.S. Bureau of Reclamation (Stamm, 1967), as presented by Montoro et al. (2011) and Pascual-Seva et al. (2016). The ETc (mm) was calculated from the ETo and a single crop coefficient (K_c) proposed for local conditions by the Instituto Valenciano de Investigaciones Agrarias (IVIA, 2011), adapting the duration of each stage to the growing cycle (Table 3).

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc}$$

where ETo is the reference evapotranspiration and Kc is the crop coefficient. The ETo was determined according to Allen et al., (1998) as follows:

$$\mathrm{ETo} = E_{pan} \times K_{pan}$$

where E_{pan} (mm day^{-1}) is the evaporation from the Class A pan installed in the Experimental Center and K_p (0.815) is the pan coefficient, determined according to Allen et al. (1998).

The water was supplied by a drip irrigation system with one line, on the soil surface, per bed with emitters spaced 0.30 m apart and a discharge of 2.2 L h^{-1}. The amount of water applied for each irrigation event was recorded using totalizing water flow meters connected to the irrigation system. The irrigation events of T1 began when the volumetric soil water content (VSWC) descended to the value of 80% of field capacity, and the other strategies were irrigated at the same time, with the corresponding reductions in irrigation water applied ($I_{applied}$).

2.4. Volumetric soil water content

The VSWC (m^3 m^{-3}) was continuously monitored using ECH$_2$O EC-5 capacitance sensors connected to an Em50 data logger using the ECH$_2$O Utility software (Decagon Devices Inc., Pullman WA., USA). The sensors were installed one day before transplanting and placed horizontally in the middle of the beds below the irrigation tubing and equidistant between the two emitters, at a 0.15 m depth for all treatments. Additionally, two sensors were installed at a 0.30 m depth for the two extreme strategies, T1 and T3, following the methodology described by González et al. (2009). The VSWC was measured and stored at 15 min intervals. The factory sensor calibration was used directly in the experiments to determine the VSWC. However, in order to compare different irrigation strategies and depths, it was decided to present the VSWC evolution throughout the growing season, as the ratio of the VSWC at each moment compared with VSWC at field capacity (% FC).

2.5. Experimental design and measurements

Each irrigation strategy was replicated three times in a random block design with each replication consisting of a bed (30 m^2). The external plots were surrounded by similar plots to eliminate border effects.

Three representative plants were sampled from each elemental plot at the end of the growth cycle. Aboveground plants were divided into two parts and analyzed separately: vegetative, including shoots with all their leaves (hereinafter referred to as shoots), and reproductive, including fruits. Each sampled plant part (shoots and fruits) was weighted with a precision analytical balance (Mettler Toledo AG204), dried at 65°C in a forced-air oven (Selecta 297; Barcelona, Spain) until reaching a constant weight to obtain dry weights and dry matter content.

The chlorophyll index (SPAD) allows the indirect and non-destructive evaluation of the content of leaf chlorophyll by light intensity absorbed by the tissue sample. The SPAD was measured at the end of the growth cycle at three points in each of three fully developed leaves in each plant using a SPAD-502 m (Konica Minolta Sensing Inc., Tokyo, Japan).

Total cumulative fruit yield was separated into marketable and non-marketable yield. Marketable yield was classified in accordance with the standard classification, based on the weight usually used in Spain for this watermelon type, that considers fruits less than 4 kg as small (non-marketable) and those greater than 7 kg as large fruits (marketable). The average fruit weight and number of fruits were determined. The harvest index (HI) was determined as the ratio of marketable yield to total aboveground biomass, both on a dry mass basis (g g^{-1}; Turner, 2004).

Three representative fruits per plot were selected to determine the size (height and width) and shape (relation of height/width) of the fruits. Thereafter, fruits were cut to determine rind thickness, and soluble solid content (SSC; º Brix) was assessed with juice obtained from the central part of the fruit using a digital refractometer (Atago®, Pal-1, 0-53%, Japan). Fruit color coordinates (L*, a* and b*) were taken at the central part of the fruits using a Minolta CR-300 chroma meter (Konica Minolta Sensing Inc., Tokyo, Japan). L* represents the luminosity, with values ranging from 0 to 100. With a* and b* values, the Hue angle (Hº) and Chroma (C) were calculated as H° = Arctang (b/a) (McGuire, 1992) and $C = \sqrt{(a^2+b^2)}$ (Pathare et al., 2013), respectively.

2.6. Irrigation water use efficiency and yield response factor

The IWUE was calculated as the ratio of marketable yield (fresh mass; kg m^{-2}) to $I_{app\ lied}$ (m^3 m^{-2}; Cabello et al., 2009).

The yield response to water deficits during the growing season and each growth stage was determined according to Doorenbos and Kassam (1979), using the following equation:

$$\left(1-\frac{Y_a}{Y_m}\right) = k_y \left(1-\frac{ET_a}{ET_m}\right)$$

where Ya and Ym are the actual and maximum marketable yield (kg m^{-2}), respectively; ETa and ETm are the actual and maximum ET (mm), respectively; and k_y is the yield response factor. ETa and ETm were calculated using the soil water balance: ET = $I_{applied}$ + Pe, considering negligible both the drainage and the variation in the volumetric soil water content. Values of Ky greater than 1 indicate that the crop response is very sensitive to water deficit, while values of Ky lower than 1 mean that the crop is more tolerant to water deficit. When Ky is equal to 1, yield reduction is directly proportional to reduced water use (Doorenbos and Kassam, 1979; Steduto et al., 2012).

2.7. Relative water content and membrane stability index

The relative water content (RWC; %) was determined in fresh leaf discs of 2 cm^2 diameter. The discs were weighed (fresh mass; FM), and immediately floated on double-distilled water in Petri dishes to saturate them with water for 6 h in darkness. The adhering water of the discs was blotted, and turgor mass (TM) was recorded. The dry mass of the discs was noted after dehydrating them at 70°C for 48 h. RWC was calculated using the following formula (Hayat et al., 2008):

$$\text{RWC (\%)} = \frac{\text{FM} - \text{DM}}{\text{TM} - \text{DM}} \times 100$$

The membrane stability index (MSI; %) was determined for 0.2 g samples of fully expanded leaf tissue (Rady, 2011). The leaf sample was placed in a test-tube containing 10 ml of double-distilled water. The content of the test-tube was heated at 40°C in a water bath for 30 min, and the electrical conductivity (C_1) of the solution was recorded using a multi-parameter analyzer Consort C830 (Consort B2300; Turnhout, Belgium). A second sample was boiled at 100°C for 10 min, and the conductivity was measured (C_2). The MSI was calculated using the following formula (Rady, 2011):

$$\text{MSI (\%)} = [1 - (C_1/C_2)] \times 100$$

Both RWC and MSI were determined by duplicate in each field replication, at the end of each growth stage.

2.8. Statistical analysis

The results of the two experiments were analyzed separately. In the first experiment, T1, T2 and T3 were compared for both years, while in the second experiment, all IR in 2017 were compared. The results were analyzed using an analysis of variance (ANOVA) using Statgraphics centurion XVII (Statistical Graphics Corporation, 2014). Least significant difference (LSD) at a 0.05-probability level was used as the mean separation test.

3. Results

3.1. Sustained deficit irrigation

The duration of each growth stage, initial, vegetative development, mid-season and late season, was 11, 28, 20 and 15 days in 2016 and 12, 30, 20 and 17 days in 2017, respectively. The total growth cycle period was 74 days in 2016 and 79 days in 2017. These values, as well as the corresponding Kc values, are presented in Table 3.

The total pan evaporation and consequently ETo during the growing season were lower in 2016 (532 and 433 mm, respectively) than in 2017 (578 and 471 mm, respectively). Values of the monthly precipitation during the two growing seasons were lower than twice the average monthly temperature (ºC; data no shown), thus the months included in the experiment are considered dry according to the xerothermic index of Gaussen (Gaussen and Bagnouls, 1952).

During the 2016 growing season T1 received 293 mm while T2 and T3 received 77 and 53%, respectively, of T1. In 2017, T1 received 321 mm while T2 and T3 received 78 and 55%, respectively. These irrigation data indicate that the treatment values of 75 and 50% irrigation rates were accomplished (Table 4). These values include 15 mm in 2016 and 20 mm in 2017 as an initial irrigation across all treatments to ensure good plant establishment.

Figure 2 shows the VSWC for T1, T2 and T3 in 2016 and 2017, as well as the Pe. Rain was scarce during the two years, particularly in 2016. Generally, VSWC in the three treatments was relatively higher in 2016 (on average 87.5% FC) than in 2017 (on average 84.7% FC), probably because the soil profile was sandier in 2017 (the sand content was practically two times that in 2016), leading to a higher permeability and less retention of the water supplied on the surface layer. VSWC at a 0.15 m depth was higher under T1 as compared to under T2, which in turn was higher than under T3 (on average 92.5, 89.5 and 76.4 % FC, respectively). T1 had a higher VSWC at a 0.30 m depth (on average 90.9% FC) than that of T3 (on average 82.2% FC), which showed a decreasing trend in their VSWC over time.

Table 5 shows the results of the total yield (in terms of kg m^{-2}, fruit number m^{-2}, and average fruit weight), marketable yield (indicating the percentage of large fruits), non-marketable yield (differentiating sunburned and small fruit production, which are the only types of culls that were found) and IWUE during the 2016 and 2017 seasons. Water restriction negatively affected ($P \leq 0.01$) yield and yield components, but none of the parameters were affected ($P \leq 0.05$) by the growing season. The interaction between both factors was not significant ($P \leq 0.05$) for any of the analysed parameters. T1 resulted in a higher ($P \leq 0.01$) total yield, average fruit weight and total marketable yield compared to T3, with intermediate values for T2. T1 led to a greater ($P \leq 0.01$) proportion of large fruits than T2 and T3. Non-marketable yield represented 55% of the total yield for T3, while it was 11% for T1. Analyzing the different fruits considered as non-marketable, T3 led to a higher ($P \leq 0.01$) yield of small fruits compared to that of T2 and T1. Although the sunburned fruit weight was not significantly different among IR, it increased as $I_{applied}$ decreased. The IWUE values were high, which corresponds to high-yield crops, and they were affected by IR, with the highest value corresponding to the full irrigation treatment and the lowest to T3. These values are related to the important marketable yield loses of T3 compared to the water saving achieved in relation to T1 (Table 6). Marketable yield (MY) increased linearly with $I_{applied}$, following the expression MY = 0.0293 $I_{applied}$ - 2.1171, which presented a correlation coefficient (r) of 0.87 and was significant ($P \leq 0.01$). It also increased linearly with the VSWC (% FC), as shows the function MY = 0.2469 VSWC - 17.049 (r = 0.92; $P \leq 0.01$).

As for the yield response to water deficits, in both growing seasons, considering as maximum yield (Ym) the marketable yield obtained under T1, actual yield (Ya) corresponding to T2 and T3 strategies, and ETm and ETa corresponding to the cited yields, the fitted linear regression is as follows: 1-(Ya/Ym) = 1. 3 (1-(ETa/ETm), which presents a high correlation coefficient (r= 0.99) and statistical significance ($P \leq 0.01$). The yield response factor (k_y) was 1.3, being 1.0 for 2016 and 1.6 for 2017.

The fruit size (height and width) and the rind thickness were affected ($P \leq 0.01$; Table 7) by the irrigation treatment, with the lowest values corresponding to T3. The fruits produced in 2017 were wider ($P \leq 0.01$) than those produced in 2016, which could be related to the greater average fruit weight obtained in 2017 than in 2016 (Table 5). The rind thickness was affected ($P \leq 0.01$) by the interaction of season by IR, in the sense that the rind thickness of the fruits produced under T3 was narrower than that of the fruits under T1 and T2, only in 2016. The fruit shape (height/width ratio) was not affected ($P \leq 0.05$) by any of the analyzed factors or interaction.

The fruit quality parameters are presented in Table 8, in terms of fruit dry matter (%), soluble solid content (SSC; º Brix), color parameters L*, Hue angle and Chroma. Fruit dry matter was only affected by IR with the lowest content under T1, indicating higher water content with the full IR, as expected. IR also affected the SSC in the sense that the lowest value corresponded to T3. There was no difference in color characteristics of Hue and Chroma. L* was affected ($P \leq 0.01$) by both growing season and IR, with the highest lightness (brightness) values corresponding to 2016 and T3.

Table 9 presents the results for leaf chlorophyll content, expressed in SPAD, shoot dry matter (%), shoot and aboveground plant dry biomass and the harvest index (HI), corresponding to T1, T2 and T3 in 2016 and 2017. None of the analyzed parameters were affected ($P \leq 0.05$) by the interaction of growing season by irrigation rate. Neither leaf chlorophyll content nor shoot dry matter content were affected ($P \leq 0.05$) by growing season or IR. Regarding dry biomass, both shoots and total dry weight were affected ($P \leq 0.01$) by IR, with the highest values obtained under the full irrigation treatment. T3 had the lowest ($P \leq 0.05$) shoot dry biomass. The HI was affected by growing season ($P \leq 0.05$) and IR ($P \leq 0.01$), with the lowest values obtained in 2016 and T3.

The RWC and MSI results are presented in Table 10. RWC was affected ($P \leq 0.01$) by both growing season and IR, obtaining the highest values in 2016 and T1, which also presented the highest MSI ($P \leq 0.01$).

3.2 Regulated deficit irrigation

In the second experiment, there were no considerable differences in VSWC at a 0.15 m depth between the different IRs (Figure 3; on average 83.2% FC) or even during the water restriction stages, as the $I_{applied}$ in each irrigation event, in every strategy, exceeded the management allowed deficit (corresponding to 20% FC) of the shallower layer of the soil. The $I_{applied}$ values are presented in Table 4, with the lowest and the highest values corresponding to T3 and T1, respectively, with intermediate values for RDI.

Sustained and regulated deficit irrigation (Table 11) negatively affected ($P \leq 0.01$) the yield. The highest value of total yield was recorded ($P \leq 0.05$) under T1, and the lowest value was found under T3. Water restriction at 75% IWR during the fruit ripening stage (T6) had a lesser effect on the reduction in fruit yield with respect to full irrigation than when water restriction was applied during the crop development (T4)or fruit growth stages (T5) With the restriction of 50% (T7, T8 and T9) a similar trend was observed, but without statistical differences ($P \leq 0.05$). The greatest fruits number m^{-2} was observed under T1, not differing ($P \leq 0.05$) from T6 nor T9. T3 stood out particularly for having the lowest values of commercial yield, no large fruits (0%) and the highest production of sunburned fruits and small fruits (with no significant difference at $P \leq 0.05$).

Analyzing the different fruits considered as non-marketable, significant differences ($P \leq 0.01$) were found in the fruits affected by sunburn; the highest value was obtained with the most restrictive IR (T3), although its importance in the non-marketable yield was low. In contrast, the small fruit yield (fruits less than 4 kg in weight), between 78% and 100% of the non-marketable yield, was not affected ($P \le 0.05$) by the IR, probably due to the high variability of this parameter, with a coefficient of variation (CV; standard deviation as a percentage of the mean value) of 52.7%. The IWUE was negatively affected ($P \le 0.05$) by the sustained and regulated DI, but neither the sustained restriction to 75% (T2) nor RDI when water restriction was applied during the fruit ripening stage (T6 and T9) led to lower values than the full irrigated treatment. The lack of statistical difference ($P \le 0.05$) among the different DI strategies may be related with the high variability of the IWUE values (CV = 29.3%).

Table 12 presents the $I_{applied}$ savings and the marketable yield losses obtained using the different IRs. Considering the RDI strategies, the lowest yield losses and the greatest water savings were obtained when the water restriction was applied in the last stage of the crop cycle. The yield increased linearly with $I_{applied}$, and the positive linear relationships are presented in Table 13. Obviously, these relations are different depending on the stage in which the water restriction occurred. All the relationships were statistically significant ($P \le 0.01$) and showed high correlation coefficients, greater than 0.87. The greatest slope of these relations corresponds to the water restriction in the crop development stage. Other adjustments (i.e. polynomial, exponential, logistic) did not result in significance ($P \le 0.05$).

As for the yield response to water deficits, for the RDI strategies, there were four fitted linear regression equations: one for the sustained DI and one for each stage of irrigation restriction, considering the yields and ET corresponding to each strategy. All linear regression equations were fitted to the data with adequate correlation coefficients (r from 0.96 to 0.99) and statistical significance ($P \le 0.05$). The yield response factor (k_y) was 1.6, 1.4, 1.2 and 0.84 for sustained DI, crop development, fruit growth and fruit maturation, respectively.

None of the analysed fruit characteristics (size, shape and rind thickness) were affected ($P \leq 0.05$) by the IR (Table 14), probably due to the observed variability between the fruits under each RDI treatment. Overall, it could be stated that RDI strategies presented intermediate values to the extreme SDI strategies. The water restriction in this experiment did not affect ($P \leq 0.05$) the dry matter content, the SSC of fruits, L* or the Hue angle (Table 15), but it did affect ($P \leq 0.01$) the Chroma index. The highest values of Chroma corresponded to T6, and the lowest were obtained under T4 and T7.

Dry shoot biomass (Table 16) was affected by the IR ($P \leq 0.01$), in the sense that the greatest biomass was obtained under the full irrigation treatment, not showing statistical differences ($P \leq 0.05$) with T6 nor T9, which, in turn, did not differ ($P \leq 0.05$) from the other RDI strategies. The other parameters related to the vegetative part of the plant, such as SPAD, shoot dry matter, total above ground biomass and the HI, were not affected ($P \leq 0.05$) by the IR.

Figure 4 presents the evolution of the RWC and MSI indexes through the crop growth periods. Both indexes did not present significant differences ($P \leq 0.05$) between IR when irrigation restrictions were applied during growth development (RWC = 77.8%, MSI = 81.1% for T1). There were differences ($P \leq 0.05$; $P \leq 0.01$) in fruit growth and fruit ripening stages, with the highest values at the fruit ripening stage corresponding to the full irrigation treatment (RWC = 82.3%, MSI = 82.6%) and the lowest under T3 (RWC = 69.9%, MSI = 70.4%).

4. Discussion

The yields obtained in the present study under full irrigation treatment are considered similar to those obtained by López-Galarza et al. (2004) in greenhouse-grown triploid watermelon and those obtained by Özmen et al. (2015) in Turkey.

The notable reductions in both total and marketable yield caused by water restriction are similar to those obtained in seedless watermelon by Bang et al. (2004), Leskovar et al. (2004), and González et al. (2009) and in diploid watermelon by Erdem et al. (2001), Rouphael et al. (2008) and Kuşçu et al. (2015). Rouphael et al. (2008) found that plants grown under full irrigation (100% of ET_c) resulted in both higher fruit weight and number than those grown under 75% and 50% of ET_c. In this study, 100% irrigation had higher fruit weight and fruit numbers compared with reduced irrigation treatments where yield reduction is attributed to the decline in both the number of fruits and fruit size. Moreover, the results agree with those obtained by Bang et al. (2004), in that the marketable yield of large fruits decreased and that of small fruits increased as $I_{applied}$ decreased. Water restriction during the fruit ripening stage had a lesser effect on the reduction of fruit yield with respect to full irrigation than compared with water restrictions applied during the crop development or the fruit growth stages. The effect of water restrictions at fruit ripening was minimal because most of the fruits had reached their final size. Geerts and Raes (2009) presented the main advantage of DI to get the best response is by applying the full water requirement only during the most drought-sensitive stages.

In this research the fruit yield increased linearly with $I_{applied}$. Tolk and Howell (2003) reported both linear and curvilinear relationships and stated that nonlinear relationships are explainable if the HI varies with water deficit. In the first experiment, the HI only decreased under T3, and in the second experiment, the HI did not differ between IRs. Therefore, yield- $I_{applied}$ relationships were lineal when they were analyzed for the water restrictions in both the total cultivation cycle or during separate stages. These positive linear relationships between yield and $I_{applied}$ agree with the results obtained by Erdem et al. (2001) studying watermelon in Turkey.

IWUE is a key indicator that reveals the optimal water use for plant production. The IWUE obtained in this research for the full irrigation treatment agree with those reported by Kuşçu et al. (2015) and are slightly greater than those presented by Erdem et al. (2005), both obtained using the cv. *Crimson sweet* in Turkey. In the first experiment, with sustained water restriction, IWUE was affected ($P \leq 0.05$) by IR, with the highest IWUE value corresponding to the full irrigation treatment and the lowest to the maximum restriction (T3). Differences were significant due to the important marketable yield losses seen under T3 compared to the water saving achieved, in relation to T1. On the other hand, with RDI, the high coefficient of variation led to a decrease in the level of statistical significance, with similar results shown by Erdem et al. (2005). The lack of statistical significant differences between IRs for some parameters may be consequence of their high values of CV, which might be reduced using larger plots as stated by McCann et al. (2007). Some researchers have stated that IWUE is not affected by IR, such as Erdem et al. (2005).. However, other studies have shown that IWUE varies with $I_{applied}$, as in the sustained deficit irrigation experiment and in Kirnak et al. (2009), Kirnak and Dogan (2009) and Kuşçu et al. (2015), which state that IWUE depends on many other factors and particularly on climatic conditions.

All linear regression equations fitted to the data of ET versus yield response confirm the linear relations obtained between yield and $I_{applied}$ and agree with Erdem and Yuskel (2003) for watermelon in Turkey. The yield response factor obtained for the total growing season coincides with that obtained by Erdem and Nedim Yuksel (2003; 1.27).

Regarding fruit morphological parameters, it is remarkable that fruit dimensions increase with $I_{applied}$ when extreme rates are considered, as presented by Leskovar et al. (2004); however, there are no differences between RDI treatments, as reported by Özmen et al. (2015). These results were expected, as the analyzed fruits were randomly selected from marketable fruits harvested in their optimal ripening stage, therefore presenting similar characteristics.

Fruit dry matter content was at a minimum (ie the fruits showed the maximum fruit water content) under the full irrigation treatment. This greater water content in the fruits would result in expected lower SSC; however, higher contents were obtained under the full irrigation treatment rather than under the most restrictive treatments. These unexpected results could be related to higher carbohydrate production due to the greater photosynthetic capacity, due to the greater shoot biomass produced under full irrigation. Although SSC depends on many factors, such as genetic variability, cultural practices, etc. (Leskovar et al., 2004), according to different standards for watermelon fruit quality (USDA, 2006; United Nations, 2012), values greater than 10 ºBrix are considered to be at a very good sweetness level; thus, the values recorded for all IR in this research are considered as very good quality. The most abundant sugars in the watermelon fruit flesh are initially fructose and glucose (reducing sugars) that decrease at ripening thereby, increasing the sucrose (non-reducing sugar) concentration (Leskovar et al., 2004; López-Galarza et al., 2004).

Although total yield was reduced by 40% in comparison to the full IR, in similar proportion to the aboveground biomass, the greater proportion of non-marketable fruits led to a larger reduction in terms of marketable yield under T3 (70%). For this reason, the HI occurred the most restrictive strategy (T3) presented the lowest HI value. Overall, HI values obtained under T1 (on average 0.51) are somewhat low, and those obtained under T3 are very low, but it must be borne in mind that they have been obtained with respect to total biomass and not only vegetative biomass. These HI values are lower than those reported by Colla et al. (2006) for the cv. *Tex* in Italy and by González et al. (2009) for spring watermelon in Spain, but both determined the HI as the ratio of dry matter partitioned into all fruit (marketable and non-marketable fruits) relative to the total plant biomass, and therefore it led to greater values of HI. Leaf chlorophyll content was high in relation to the values reported in the literature for watermelon (approximately 42% obtained by Nicolae et al., 2014). It was not affected by water restrictions in any of the experiments.

Under sustained water restriction treatments, a reduction in RWC and MSI was observed, which may be attributed to the negative effect of water shortage on watermelon. Abd El-Mageed et al. (2016) noted a positive relationship between RWC and plant dry biomass in squash plants. This suggests that plants having a greater biomass can maintain a higher water content in leaves, leading to a greater tolerance to drought, as occurred in the present experiment. Our results are also in accordance with those obtained by Rouphael et al. (2008), who observed that the RWC of mini-watermelon cv. *Ingrid* decreased under deficit irrigation treatments of 50% and 75% of ET_c in comparison to 100% of ETc . Similar results were obtained by Kirnak et al. (2009), Kirnak and Dogan (2009) and Mohammadzade and Soltani (2015).

Regarding the RDI treatments, determinations were made at the end of each restriction stages. At the end of crop development, there were no differences between IR for neither RWC nor and MSI. Treatments that were subjected to a water shortage in the fruit growth stage showed the lowest RWC values. Regarding MSI, the lowest values were obtained under the treatments that subjected plants to water restrictions during the crop development or fruit growth. The negative evolution of the MSI corresponding to T3 suggests that with the maximum water restriction assayed, the leaves experienced light and permanent cellular membrane damage. These results agree with those reported by Ram et al. (2014) for watermelon seedlings, which indicated that water stress increases membrane permeability causing higher electrolyte leakage into the external medium, resulting in a decrease of MSI values. The RWC and MSI results agree with the greater (except for T1) fruit yield obtained in plants subjected to a water shortage in the fruit ripening stage. Therefore, it can be stated that if water restrictions are required, they should be applied in the fruit ripening stage.

It is important to increase irrigation water productivity throughout the world, especially in dry regions. A pathway to enhance water use efficiency in irrigated agriculture is to increase the output per unit of water (Howell, 2006), being even more important to maximize crop water productivity rather than the harvest per unit area (Ruiz-Sánchez et al., 2010). Nevertheless, considering the IWUE values obtained in 2017 and the average watermelon fruit price (0.27 € kg^{-1}; MAPAMA, 2017), in the present study conditions the application of DI in the fruit ripening stage would suppose a decrease in relation to full irrigation in both the gross revenue (19,710, 12,987 and 11,934 € ha^{-1} for T1, T6 and T9, respectively) and the economic value per unit of water consumed (6.14, 4.72 and 4.88 € m^{-3} for T1, T6 and T9, respectively), which would be greater if the water restriction were carried out in the other stages, seriously questioning the economic viability of the crop. Under limiting conditions, it would probably be interesting to apply the full requirements in a limited area rather than extending the cultivated area (Erdem and Nedim Yuksel, 2003), and to convert to other crops with higher economic value or productivity per unit of water consumed or even to more drought-tolerant crops (Evans and Sadler, 2008).

The herein presented results correspond to the seedless watermelon cv. *Stellar* F1, but it should be noted that the results for seeded cv. *Premium*, used as a pollinator, seem to show a similar trend.

5. Conclusions

The present study analyzed the effect of both sustained and regulated deficit irrigation on the growth and yield of watermelon cv. *Stellar* F1. If water is not a limiting factor, applying 100% of water requirements is advisable. Sustained deficit irrigation at 50% of the nominal crop water requirements led to application of lower water amounts, which resulted in a reduction in total and marketable yield and the average fruit weight, without increasing fruit quality. Irrigating at 75% of water requirements reduced to a lesser extend yield and IWUE than the 50% treatment (compared to full irrigation) and it could be recommended if water is scarce. For regulated deficit irrigation, intermediate results were obtained, highlighting the results obtained for applying water restrictions during the fruit ripening stage, both at 75% and 50% of the water requirements, which lead to acceptable marketable yields and could be recommended. When water is a limiting factor. two options could be recommended, either to apply these regulated deficit irrigation strategies, or to apply the full water requirements in a limited area.

6. References

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