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Regulated Deficit Irrigation to Boost Processing Tomato Sustainability and Fruit Quality

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Abstract: Improving water use efficiency is gaining relevance for the sustainability of agricultural practices. In semi-arid Mediterranean areas, recent studies highlighted that future climatic scenarios will be even more critical for crops, given the increase in water scarcity. In this context, the rationalization of irrigation water is necessary to sustain processing tomato (*Solanum lycopersicum* L.) yield and quality since this crop requires large volumes of water. The present research aimed to identify the effects of a regulated deficit irrigation (RDI) strategy on the environmental and economic sustainability and fruit technological and functional quality of the processing tomato crop in the Mediterranean area. A two-year, open-field experiment was carried out to compare full irrigation management (IRR, restoring 100% ET_c) with an RDI strategy based on restoring 50% ET_c when the first fruit cluster reached the typical size (BBCH 701 phenological stage, relative to Solanaceous fruits). Remarkable water saving (21.46%, average of the two years) was achieved under RDI without significant variations in total and marketable yield compared to the IRR regime. Consequently, improved economic water productivity (+23.17%) was observed, allowing enhanced processing tomato sustainability. The RDI strategy boosted the glucose content (+17.78%), soluble solids content (SSC, +10.17%), and dry matter of the fruits (+10.03 g%). Furthermore, a higher SSC-to-titratable acidity ratio (+15.47%) and a negative shift in fructose/glucose balance (−7.71%) were observed in RDI-treated plants. Higher levels of the drought stress markers proline (+38.99%) and total polyphenols (+20.58%) were detected in RDI- compared to IRR-irrigated tomato fruits. These findings suggested the RDI strategy as an effective and sustainable approach for increasing both water productivity and the fruit quality of the processing tomato crop under semi-arid Mediterranean climatic conditions.

Keywords: *Solanum lycopersicum* L.; water productivity; soluble solids content; polyphenols; proline

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1. Introduction

Among the horticultural species, processing tomato (*Solanum lycopersicum* L.) is the first yielding crop in the Italian context within the Capitanata district (Southern Italy), contributing to 25% of the national yield [1]. In 2023, over 74 thousand hectares were cultivated and 5.4 million tons of fresh product were transformed, ranking Italy among the top three producing countries worldwide [1,2].

Tomatoes and tomato products are essential for the human diet as they provide antioxidants and phenolic compounds [3]. The role of these compounds in the prevention of diseases has been reported in several epidemiological studies [3]. Polyphenols have an important role as reactive oxygen species (ROS) detoxifiers and in modulating the activity of several detoxifying enzymes involved in cancer promotion and progression through various mechanisms [4]. Kris-Etherton et al. (2002) [5] also showed that polyphenols can reduce the risk of cardiovascular disease.

Processing tomato is a high-water-demanding crop (400 and 600 mm), and its requirements are mainly replenished by irrigation since rainfall does not compensate for crop water demand throughout the growing season [6]. Although favorable weather conditions, including solar radiation and optimal temperatures, have historically allowed the spread of most horticultural crops in semi-arid climates (e.g., the Mediterranean basin) [7], approximately 20% of the European territory is currently facing drought warning conditions [8]. A wide range of Mediterranean areas are now experiencing high or extremely high water depletion [9], which may be exacerbated by climate change. According to a recent study by Cammarano et al. (2022) [10], future scenarios are projected to increase processing tomato crop water requirements in the Capitanata district due to an increase in air temperature and a severe decrease in total rainfall by the end of the century.

Irrigation scheduling for water-saving purposes will be of growing importance for tomato cultivation [11,12]. These practices include deficit irrigation (DI) and regulated deficit irrigation (RDI). DI is an approach that uniformly reduces the applied irrigation to below the crop water requirement throughout the growing season [13,14]. RDI provides adequate water only during critical development periods that may affect yields [15,16]. The effectiveness of water-saving techniques may vary depending on seasonal weather conditions, cultivation site, genotype, fertilization management, and the timing of deficit induction [17–20]. In Mediterranean and semi-arid environments, DI and RDI would save water resources and increase water productivity [21]. Studies have shown that the controlled reduction of irrigation volumes after the flowering phase of tomatoes improves fruit quality, although production may be reduced [17]. DI and RDI also have a positive effect on tomato functional value. Recent research highlighted how various levels of DI may improve amino acids, organic acids, and mineral elements in tomato fruits [22]. Martí et al. (2018) [19] reported an enhanced concentration of secondary metabolites such as L-ascorbic acid (vitamin C) and phenolic compounds (chlorogenic and ferulic acids) in RDI-treated fruits, while positive effects on carotenoids were observed by Favati et al. (2009) [12]. A higher level of these bioactive compounds in tomatoes would result in products that are more appealing to customers and beneficial for human health.

To our knowledge, no study has focused on the physiological effects of RDI on the accumulation of amino acids in tomato fruits. The latter would reflect changes in the physiological response of tomato plants to water stress [23]. Additionally, few studies have evaluated how RDI comprehensively affects the four main valuable traits (pH, titratable acidity, soluble solids content, and dry matter) for tomato processing industries [17–19].

Thus, the aim of the present work was to assess whether the effects of an RDI strategy would help to enhance the (i) environmental and economic sustainability, (ii) fruit technological quality, and (iii) fruit metabolic profiling of the processing tomato crop in the Mediterranean area.

2. Materials and Methods

2.1. Experimental Design and Crop Management

An open-field trial was carried out across two cropping seasons (2019 and 2020) at Foggia (41°32′49.0704″ N, 15°36′14.1192″ E; 43 m a.s.l.). Two irrigation strategies (full-irrigation, IRR; regulated deficit irrigation, RDI) were compared in a randomized block design with three replicates.

Seedlings of 'H1534' F1 tomato hybrid [Furia Seed, Monticelli Terme (PR), Italy] were transplanted at the four-leaf stage on 2 May 2019 and 18 May 2020 (Table S1) in 4 m long paired rows. Each plot consisted of seven twin rows spaced 1.8 m apart, with a distance of 0.40 m between each row of the twin and 0.40 m between seedlings in the row, corresponding to a final plant density of 2.78 plants m^{-2} (Figure 1).

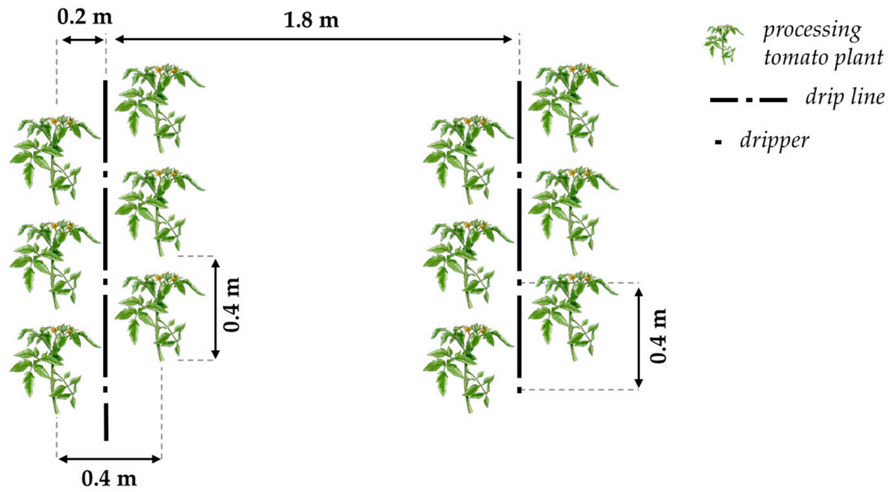


Figure 1. Plant and row spacing and drip line positioning in the open-field trial.

The fertilization scheduling (123 kg ha^{-1} of N, 92 kg ha^{-1} of P2O5, and 80 kg ha^{-1} of K_2O in 2019; 127 kg ha^{-1} of N, 77 kg ha^{-1} of P_2O_5, and 110 kg ha^{-1} of K_2O in 2020) was established considering the soil analysis and nutrient requirements in the different phenological stages and based on the expected fruit yield. Pest management and weed control were performed according to the cultivation guidelines of the Apulia Region (Italy).

A single harvesting took place on 21 August 2019 and 3 September 2020, when marketable fruits accounted for 85% of the total production. In 2019, the crop cycle lasted 111 days, corresponding to 1346 growing degree days (GDD), while, in 2020, the length of the cycle was 108 days, accounting for 1409 GDD.

All acronyms cited in the present paper are reported in Table 1.

Table 1. Alphabetically ordered acronyms included in the present work and their description.

Acronym	Description
BERY	Fruits affected by blossom-end rot
BrY	Brix yield
CRACK	Cracking fruits
DAT	Days after transplanting
DM	Fruit dry matter
EWP	Economic water productivity
FC	Soil water content at field capacity
FDB	Fruit dry biomass
FDR	Dry matter distribution rate for FDB
Fru	Fructose
Fru/Glc	Fructose-to-glucose ratio
FRW	Average fruit weight
FW	Fresh weight
GDD	Growing degree day
Glc	Glucose
GY	Unripe fruits
HI	Harvest index
IRR	Full-irrigation management
Lyc	Lycopene

Table 1. *Cont.*

Acronym	Description
MY	Marketable yield
NFR	Number of marketable fruits per plant
PP	Polyphenols
Prot	Proteins
RAW	Readily available water
RDI	Regulated deficit irrigation
RY	Rotten fruits
SSC	Soluble solids content
SSC/TtA	Soluble solids-to-titratable acidity ratio
SsF	Sunscald fruits
Sta	Starch
Suc	Sucrose
SWC	Soil water content in volume
SWD	Soil water deficit
TADB	Total aboveground dry biomass
TDF	Total defective fruits
TtA	Titratable acidity
TY	Total yield
VDB	Vegetation dry biomass
VDR	Dry matter distribution rate for VDB
VrF	Fruits with viral symptoms
WP	Soil water content at wilting point
WP_I	Irrigation water productivity
WY	Unmarketable fruits

2.2. Soil Parameters

Before the transplanting, soil was sampled from each block in three replicates to determine the physical and chemical characteristics of the upper soil layer (0–40 cm). Since no significant differences were identified between the two blocks, the average values of the physical and chemical characteristics of the soil are reported in Table S1. Soil texture was classified as clay-loam [24] with 41% sand, 20% silt, and 39% clay. Soil water content at field capacity (FC) and wilting point (WP) were 0.344 m^3 m^{-3} and 0.196 m^3 m^{-3}, respectively.

2.3. Irrigation Management and Treatments

Two irrigation treatments (IRR and RDI) were compared in the open-field trial:

- IRR: the control treatment, restoring 100% of crop evapotranspiration. Irrigation occurred when ready water availability was exhausted, in accordance with Allen et al.'s (1998) methodology [25]. Crop evapotranspiration was calculated as ETc = $ET_0 \times$ Kc, where ET_0 (reference evapotranspiration) was estimated with the Penman–Monteith method, according to Allen et al. (1998) [25], and Kc is the tabulated crop coefficients (Kcini = 0.15; Kcmed = 0.90; Kcend = 0.20). A depletion fraction value of 0.45 was adopted. Correction of Kcini (for precipitation events), Kcmed, and Kcend (for climatic conditions and crop height) was performed according to Allen et al. (1998) [25].
- RDI: regulated deficit irrigation. RDI treatment followed IRR scheduling (100% ETc) up to the BBCH 701 phenological phase (relative to Solanaceous fruits, when the first fruit cluster has reached the typical size) [26]. Once BBCH 701 was reached, RDI irrigation volume was reduced by 50% compared to IRR volumes [26]. Soil water content in volume (SWC) was measured by capacitive probe 10 HS sensors (Meter Group Inc., Pullman, WA, USA). For each treatment, three points were monitored. At each point, two capacitive probes were installed horizontally into the soil profile and transversely to the row, at −0.20 and −0.40 m from the soil surface, to intercept the dynamics of SWC below the dripping lines. All sensors were connected to data-loggers (Tecno.el SRL, Rome, Italy) and data were transferred to a web server via GPRS mode. Soil water deficit (SWD, Equation (1)) was calculated as follows [27]:

$$\text{SWD}[\%] = \left[1 - \frac{\text{SWC} - \text{WP}}{\text{FC} - \text{WP}}\right] \times 100 \quad (1)$$

A drip irrigation system was adopted, with a single plastic drip line lying in the middle of each twin row and spaced 0.2 m from plant rows (Figure 1). Drippers had a 2 L h^{-1} individual flow rate and were distanced every 0.4 m. Irrigation water, following FAO guidelines for agricultural purposes [28], was supplied by 'Consorzio per la Bonifica della Capitanata' throughout the whole trial.

As reported in Table 2, in 2019, a total of 4640 and 3520 m^3 ha^{-1} was supplied in IRR and RDI, respectively, through 22 irrigation events beginning on 8 May 2019 and ending on 14 August 2019, with 11 irrigation events occurring after inducing RDI (6 July 2019). In 2020, a total of 3694 and 3000 m^3 ha^{-1} was supplied in IRR and RDI, respectively, through 19 irrigation events beginning on 25 May 2020 and ending on 21 August 2020, with 7 irrigation events occurring after inducing the RDI (29 July 2020).

Table 2. Irrigation management of the open-field trial and irrigation volumes supplied to the crop for IRR (full irrigation) and RDI (regulated deficit irrigation) in the 2019 and 2020 growing seasons.

Season	Seasonal Irrigation Duration (Days)	No. of Irrigations	Turn (Days)	RDI Induction			IRR		RDI	
				Date	DAT	GDD	Total Volume (mm)	Depth (mm)	Total Volume (mm)	Depth (mm)
2019	98	22	4	6 July 2019	65	659	464	21	352	16
2020	88	19	5	29 July 2020	72	864	369	19	300	16

DAT = days after transplant, GDD = growing degree days, Turn = average interval among irrigation events, Depth = average irrigation volume per turn (total volume/no. of irrigations).

2.4. Weather Conditions

The meteorological data were recorded by a weather station located near the experimental farm. The local climate was classified as semi-arid, according to Francaviglia et al., 2019 [29], and De Martonne's aridity index was 17.92 and 17.00 mm °C^{-1} in 2019 and 2020.

Key climatic data for 2019 and 2020 are shown in Figure 2a,b, respectively. During the 2019 season, the total rainfall was 102.0 mm, with 38.0 mm falling after the beginning of the RDI phase (2 rainfall events). The maximum temperature was 29.3 °C, on average, with the highest value reaching 38.8 °C; the minimum temperature was 16.9 °C, on average, and the lowest value was 4.5 °C; the overall average temperature for the year was 23.1 °C. In 2020, the total rainfall decreased to 89.0 mm, with 37.2 mm falling after the beginning of the RDI phase (2 rainfall events). Air temperatures were higher than in 2019; indeed, the maximum temperature was 30.1 °C, on average, with the highest value reaching 38.7 °C; the minimum temperature was 17.7 °C on average, and the lowest value was 10.1 °C; the overall average temperature for the year was 23.9 °C.

2.5. Crop Growth

Starting one month after transplanting, the crop growth was assessed at five (2019) and six (2020) sampling times, both in terms of vegetation (stems and leaves, as a sum) and yield (fruits). Plant samples (3 plants per treatment) were dried in a stove at 65 °C until a constant weight was achieved and weighed (VDB, vegetation dry biomass, t ha^{-1}; FDB, fruits dry biomass, t ha^{-1}). The total aboveground biomass (TADB) was derived as the sum of VDB and FDB, and the dry matter distribution rates for the vegetative part (VDR) and fruits (FDR) were calculated as the percentage of TADB [30]. Then, the FDR measured at harvesting corresponded to the crop harvest index (HI) [31].

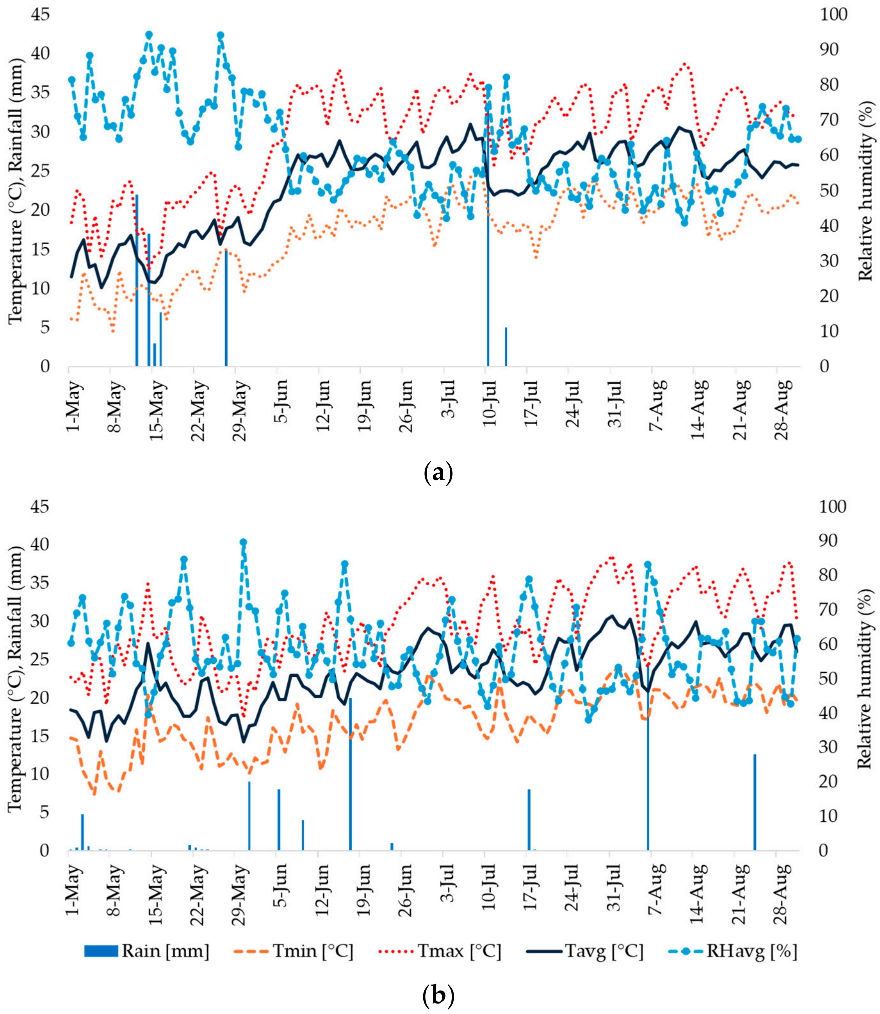


Figure 2. Weather conditions in 2019 (**a**) and 2020 (**b**), reported as daily values. Rain = rainfall events, Tmin = minimum air temperature, Tmax = maximum air temperature, Tavg = mean air temperature, RHavg = mean air relative humidity.

2.6. Yield, Fruit Defects, and Crop Sustainability

Total yield (TY), marketable yield (MY, fully ripe), and unmarketable fruits [WY, as the sum of GY (unripe), RY (rotten), and BERY (blossom-end rot)] were assessed for each plot according to Fusco et al. (2023) [32] and expressed as t ha^{-1}. A sample of 100 ripe fruits was collected to determine the average fruit weight (FRW, g) and the incidence (%) of defective fruits (TDF), categorized as sunscald (SsF) and cracking fruits (CRACK) and fruits with viral symptoms (VrF), as described by Parisi et al. (2022) [33]. MY was then divided by FRW to calculate the average number of marketable fruits per plant (NFR). The irrigation water productivity (WP_I, Equation (2)) [34] and economic water productivity (EWP, Equation (3)) [35] were calculated as follows:

$$WP_I\left(\text{kgm}^{-3}\right) = \frac{TY}{I} \quad (2)$$

$$EWP(\text{EUR m}^{-3}) = \frac{MY \times Price - I \times Cost_I - Fuel \times Cost_F}{I} \quad (3)$$

where I is the seasonal irrigation volume (m^3 ha^{-1}), Price is the price paid for marketable yield (EUR 150/t^{-1}), Fuel is the amount of fuel used for irrigation practices (3.5 L h^{-1}), $Cost_I$ is the cost per unit of Irrigation (EUR 0.13/m^{-3}), and $Cost_F$ is the cost per unit of

Fuel (EUR 1.18/L^{-1}). These referred to the mean values for the Capitanata district in 2023 (M. Caroppi, personal communication, 23 January 2024).

2.7. Fruit Analyses

Thirty fully ripe and disease-free fruits (around 2 kg) per plot were washed, dried at room temperature, and then homogenized for 1 min in a Waring blender (2 L capacity; Model HGB140, PartsTown, Addison, IL, USA). Each homogenized fresh sample was divided into two aliquots of 50 mL. One was stored at −20 °C for technological analysis; the other was rapidly frozen in liquid nitrogen and stored at −80 °C for fruit metabolic profiling. The latter was sent on dry ice to the Plant Crop Physiology laboratory of the University of Campania "Luigi Vanvitelli" and then prepared for assays according to Fusco et al. (2023) [32].

2.7.1. Technological Traits

A pH-Matic 23® titroprocessor equipped with a pH electrode model 5011T (Crison Instruments, Barcelona, Spain) was employed for the determination of pH and titratable acidity (TtA, g of citric acid per 100 g of juice or g% CA) (Merck Life Science, Darmstadt, Germany) on a sample of 5 g of aliquot stored at −20 °C. Soluble solids content (SSC, °brix on 100 g of juice) and fruit dry matter content (DM, g of dry matter on 100 g of juice or g%) were assessed according to Fusco et al. (2023) [32]. Based on these parameters, two quality indexes were calculated: soluble solids-to-titratable acidity ratio (SSC/TtA) [33] and brix yield (BrY, t ha^{-1}), by multiplying MY by SSC and dividing the result by 100 [36].

2.7.2. Starch and Soluble Sugars Analysis

Aliquots of 20 mg of tomato sample were subjected to two successive extractions with 150 mL of 80% (v:v) ethanol and a final extraction with 150 mL of 50% (v:v) ethanol at 80 °C for 25 min. Then, samples were centrifuged at 14,000× g for 10 min at 4 °C. Starch present in the pellet of ethanol extracts was hydrolyzed by the addition of 200 mL of 0.1 M KOH and heated for 2 h at 95 °C. After cooling on ice, the samples were acidified to pH 4.5 with acetic acid; mixed 1:1 with a hydrolysis buffer containing 50 mM sodium acetate pH 4.5, a-amylase 2 U mL^{-1}, and amyloglucosidase 20 U mL^{-1}; and incubated for 18 h at 37 °C. The samples were centrifuged at 14,000× g for 10 min at 4 °C and the supernatant containing the glucose derived from the hydrolyzed starch was used for measurement. As for the soluble sugars (glucose, fructose, and sucrose), the analysis was carried out on the clear supernatants derived from the three ethanol extractions and stored at −20 °C until the sugar analysis. According to Carillo et al. (2019) [37], an enzymatic assay coupled to pyridine nucleotide reduction was used to determine the glucose, fructose, and sucrose content in ethanol extracts and starch-derived glucose. The sugar content was expressed in mg g^{-1} FW. The fructose-to-glucose ratio (Fru/Glc) was then derived.

2.7.3. Polyphenols and Lycopene Analysis

Polyphenols were determined according to Singleton et al. (1999) [38] with the modifications reported in Fusco et al. (2023) [32]. The total phenols content in the samples was assessed by employing a standard curve derived from known concentrations of gallic acid (GAE) and expressed as mg GAE 100 g^{-1} FW.

The lycopene content was determined according to Sadler et al. (1990) [39] with the modifications reported by Fusco et al. (2023) [32]. Lycopene concentration was determined by comparing it with a standard curve obtained with known concentrations of pure lycopene and expressed as µg 100 g^{-1} FW.

2.7.4. Soluble Proteins and Free Amino Acid Analysis

Tomato samples (20 mg) were extracted using a buffer containing 500 mM $MgCl_2$ and 200 mM TRIS- HCl pH 7.5 and then stored for 24 h at 4 °C. After centrifugation at 14,000× g at 4 °C for 10 min, aliquots of clear supernatants (20 µL) were mixed (1:10 v:v) with concentrated protein assay reagent (Bio-Rad, Milan, Italy) diluted with H_2O milli Q (1:5 v:v). The soluble protein content was assessed by using known concentrations of bovine serum albumin (BSA) standard curves as a reference standard and expressed in mg g^{-1} FW, according to Bradford et al. (1976) [40]. Free amino acids were extracted from 20 mg of fresh tomato fruit in 1 mL ethanol/water (40:60 v:v) overnight at 4 °C and estimated by HPLC after pre-column derivatization with *o*-phthaldialdehyde (OPA), in accordance with Dell'Aversana et al. (2021) [41]. Proline was determined in the same extract according to Dell'Aversana et al. (2021) [41]. Free amino acids and proline were expressed in µmol g^{-1} FW.

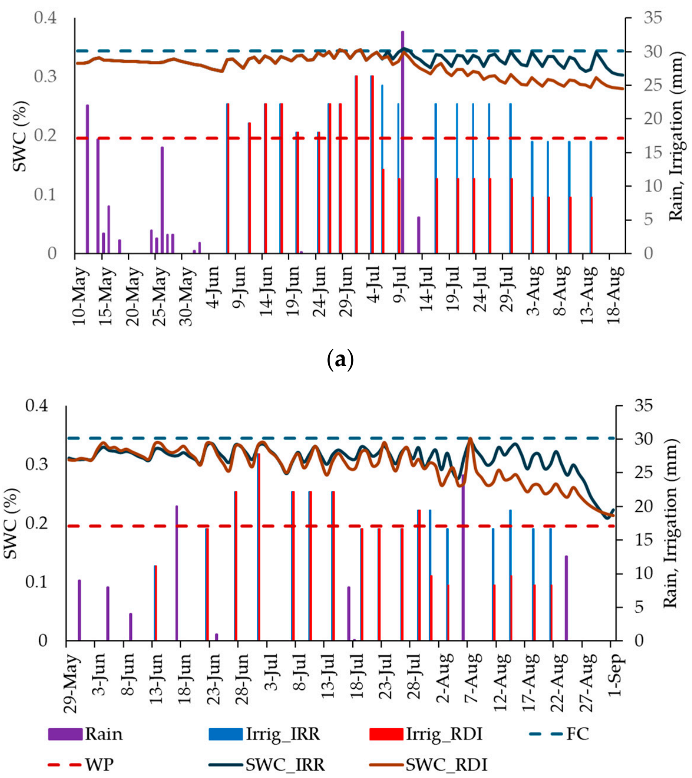
2.8. Data Analysis

RStudio 2023.06.0 + 421 "Mountain Hydrangea" was employed for statistical analysis. The Shapiro–Wilk test was used to assess the distribution normality of standardized residuals in continuous variables, while transformations were applied to variables that did not exhibit a normal distribution of residuals. Analysis of variance (two-way ANOVA) for Year (Y), Treatment (T), Y × T interaction, and blocks was then run ($p < 0.05$). Since the effect of blocks was not significant, mean values for Y, T, and Y × T were considered and separated through Duncan's test ($p \leq 0.05$). Principal component analysis (PCA) was carried out using Minitab 18 statistical software (Minitab LLC, State College, PA, USA).

3. Results

3.1. Soil Water Content

In 2019, the soil water content (SWC) in RDI showed a different trend compared to IRR starting from mid-July, corresponding to the reduction in irrigation volumes (Figure 3a).



(**a**)

(**b**)

Figure 3. Soil water content, rainfall, and irrigation volumes recorded in (**a**) 2019 and (**b**) 2020. Rain = rainfall events, Irrig_IRR = irrigation events in IRR treatment, Irrig_RDI = irrigation events in RDI treatment (mm), FC = field capacity, WP = wilting point, SWC_IRR = soil water content recorded in IRR treatment, SWC_RDI = soil water content recorded in RDI treatment (%).

The precipitation event on 10 July 2019 (33.0 mm) replenished the soil water content at field capacity (FC), even for the RDI treatment. The SWC in the IRR treatment reached the FC values after each irrigation event. In contrast, the RDI strategy resulted in a constant reduction in SWC values, which progressively approached the threshold of readily available water (RAW) (0.285 m^3 m^{-3}).

As in the previous year, in 2020, the SWC displayed different patterns in IRR and RDI starting from late July, after the reduction in irrigation volumes for the RDI treatment (Figure 3b). The SWC trend for IRR management consistently remained above the RAW threshold throughout most of the crop cycle due to an optimal supply of water volume. In the RDI strategy, the SWC values remained below the RAW from the first days of August onwards, inducing soil water stress conditions. The precipitation event on 6 August 2020 (24.6 mm) brought the SWC near the FC level, even for the RDI treatment.

3.2. Crop Growth

The effect of regulated deficit irrigation on aboveground dry biomass accumulation was assessed in both 2019 and 2020 (Figure 4).

In the first season (2019), the RDI strategy did not affect TADB and VDB throughout the whole crop cycle compared to IRR management. The maximum values of TADB and VDB for IRR (21.05 and 12.28 t ha^{-1}, respectively) were recorded at 81 days after transplanting (DAT), followed by a linear decrease up to harvesting. At this sampling, the maximum VDB gap between RDI and IRR (−25.61%) was observed, although no statistical differences were noted. The highest level of VDB was observed at 91 DAT (9.52 t ha^{-1}). A *plateau* in VDB was reached five days after the beginning of the water deficit phase (70 DAT) with RDI treatment, when the only significant difference in VDR (61.32% for IRR and 67.09% for RDI) and FDR (38.68% for IRR and 31.91% for RDI) was observed. As for FDB accumulation, a rapid increase was observed up to 81 DAT (8.77 and 6.89 t ha^{-1} for IRR and RDI, respectively), when the highest gap between RDI and IRR was detected (−21.40%). After this sampling, slight growth was detected in both treatments, with RDI allocating dry biomass to fruits at a higher rate (−1.96% FDB gap at harvest compared to IRR).

In the second season (2020), the RDI strategy lowered TADB starting from 79 DAT, although VDB was never affected by irrigation management throughout the whole crop cycle. The maximum value of VDB for IRR (3.58 t ha^{-1}) was recorded at 93 DAT, followed by a slight decrease up to harvesting. At 79 DAT, the greatest TADB gap between RDI and IRR (−21.14%) was observed. A plateau in VDB was reached at 71 DAT for RDI. As for FDB accumulation, a continuous increase was detected up to harvesting in both treatments, with the highest gap between RDI and IRR observed at 79 DAT (−30.63%).

After this sampling date, an increase observed in RDI treatment led to a reduction in the final FDB gap (−13.67% at harvest compared to IRR). Significant differences in VDR were only noted at 53 DAT (30.54% in IRR and 18.36% in RDI).

3.3. Crop Yield and Sustainability

As reported in Table 3, irrigation management affected HI, WP_I, and EWP. Although HI was slightly decreased by the RDI strategy (−0.70%), WP_I and EWP were positively influenced by RDI, respectively increasing by +21.89% (29.54 kg m^{-3} vs. 24.23 kg m^{-3}) and +23.17% (4.23 vs. 3.43 € m^{-3}) with respect to IRR. The induction of a regulated water deficit did not affect the yield and its components. Significant variations were observed for all variables over the two years, except for FRW. Indeed, greater total yield (TY) and MY values were found in 2019 (151.95 and 129.05 t ha^{-1}, respectively) than in 2020 (84.53 and 71.73 t ha^{-1}, respectively). The latter yield trait accounted for 85.14% (2019) and 84.74% (2020) of TY, with no significant differences between the years (). NFR also reached the highest values in 2019 (73.73) compared to the second year of the experiment (38.91). Water productivity indexes followed the same trend, with EWP and WP_I showing higher values in 2019 (EUR 4.6 m^{-3} and 32.29 kg m^{-3}, respectively) than in 2020 (EUR 3.02/m^{-3} and 21.48 kg m^{-3}, respectively).

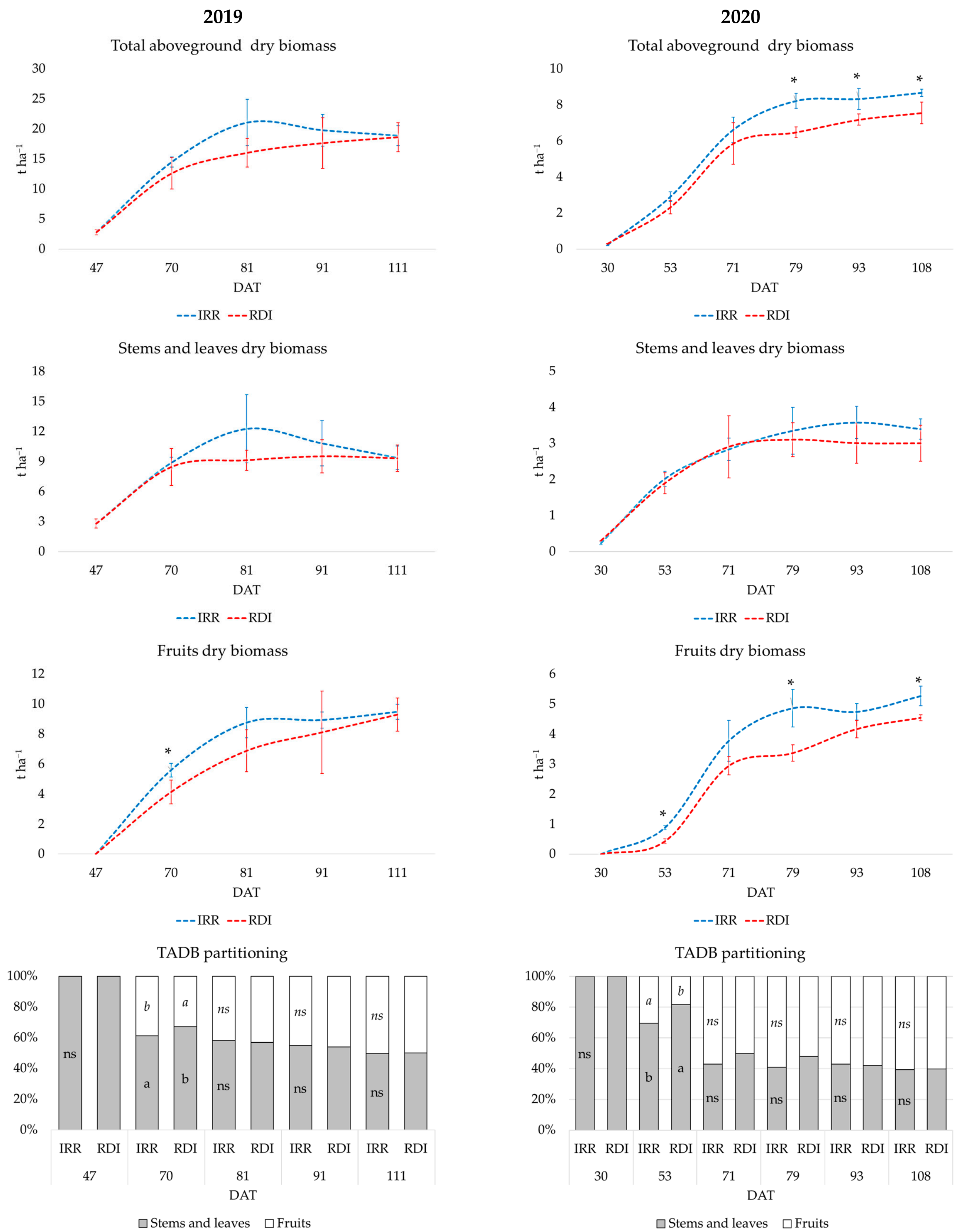


Figure 4. Crop growth assessment with IRR and RDI treatments in 2019 and 2020. DAT = days after transplanting, TADB = total aboveground biomass (t ha^{-1}). ns, * = non-significant or significant at $p \leq 0.05$, respectively. Different letters within each stacked column indicate significant differences between treatments according to Duncan's test ($p \leq 0.05$), with bold referring to stems and leaves partitioning and italics referring to fruits partitioning.

Table 3. Effects of Treatments (IRR = full irrigation, RDI = regulated deficit irrigation), Year (2019–2020), and Treatment × Year interaction on yield components, harvest index, and irrigation and economic water productivity (cv "Heinz 1534").

	FRW (g)	NFR (n pt^{-1})	TY (t ha^{-1})	MY (t ha^{-1})	WY (t ha^{-1})	RY (t ha^{-1})	BERY (t ha^{-1})	GY (t ha^{-1})	HI	WP_I (kg m^{-3})	EWP (EUR m^{-3})
Treatment											
IRR	66.11 a	57.11 a	121.37 a	102.50 a	18.87 a	3.42 a	2.15 a	13.30 a	0.56 a	28.62 b	3.43 B
RDI	63.23 a	55.53 a	115.12 a	98.27 a	16.84 a	4.45 a	2.51 a	9.88 a	0.55 b	34.67 a	4.23 A
Year											
2019	63.03 a	73.73 a	151.95 a	129.05 a	22.91 a	1.79 b	0.95 b	20.16 a	0.50 b	37.91 a	4.64 A
2020	66.31 a	38.91 b	84.53 b	71.73 b	12.80 b	6.08 a	3.71 a	3.02 b	0.61 a	25.38 b	3.02 B
Treatment × Year											
IRR × 2019	61.29 b	74.77 a	153.48 a	127.33 a	26.16 a	2.21 a	1.00 a	22.95 a	0.50 a	33.08 b	3.91 A
RDI × 2019	64.77 ab	72.69 a	150.42 a	130.76 a	19.66 a	1.38 a	0.91 a	17.38 a	0.50 a	42.73 a	5.37 A
IRR × 2020	70.93 a	39.46 a	89.25 a	77.67 a	11.58 a	4.62 a	3.30 a	3.65 a	0.61 a	24.16 c	2.95 A
RDI × 2020	61.69 b	38.36 a	79.81 a	65.79 a	14.02 a	7.53 a	4.11 a	2.38 a	0.60 a	26.60 c	3.09 A
Significance											
Treatment	ns	ns	ns	ns	ns	ns	ns	ns	*	***	*
Year	ns	***	***	***	*	***	**	***	***	**	***
Treatment × Year	**	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
Mean	64.67	56.32	118.24	100.39	17.86	3.94	2.33	11.59	0.55	31.64	3.83

FRW = average fruit weight, NFR = number of marketable fruits per plant, TY = total yield, MY = marketable yield, WY = unmarketable fruits, RY = rotten fruits, BERY = fruits affected by blossom-end rot, GY = unripe fruits, HI = harvest index, WP_I = irrigation water productivity, EWP = economic water productivity. ns, *, **, *** = non-significant or significant at $p \leq 0.05$, 0.01, and 0.001, respectively. Different letters within each column indicate significant differences between treatments, year, and treatment × year according to Duncan's test ($p \leq 0.05$).

Conversely, a greater amount of WY was recorded in 2019 (22.91 t ha^{-1}) than in 2020 (12.80 t ha^{-1}), without significant variations in the WY-to-TY ratio over the two years (14.86 and 15.26%, respectively). GY and HI recorded the same pattern, with values reaching 20.16 t ha^{-1} in 2019 and 3.02 t ha^{-1} in 2020 and 0.50 in 2019 and 0.61 in 2020, respectively. Nevertheless, RY and BERY were higher in the second year (6.08 and 3.71 t ha^{-1}, respectively) in comparison with 2019 (1.79 and 0.95 t ha^{-1}, respectively). The interaction between Treatment and Year affected FRW and WP_I, with IRR × 2020 showing greater fruits than RDI × 2020 (70.93 and 61.69, respectively) and WP_I being higher in RDI × 2019 than in IRR × 2019 (42.73 vs. 33.08 kg m^{-3}).

3.4. Fruit Defects, Technological Traits, and Brix Yield

As shown in Table 4, the RDI strategy boosted both SSC (+10.17%) and DM (+10.03%) contents with respect to the IRR strategy (5.78 °Bx and 6.85 g% for RDI and 5.32 °Bx and 6.40 g% for IRR, respectively). A significant effect of the Year factor was found for TDF, Vrf, SSC, DM, and pH. While pH decreased in 2020 with respect to the previous year (4.41 vs. 4.60,), contrasting behavior was detected for SSC and DM (5.15 vs. 5.79 °Bx and 5.84 vs. 7.11 g% for SSC and DM in 2019 and 2020, respectively). Total defective fruits (TDF) and VrF also had higher values in 2020 with respect to the previous year (31.17% vs. 5.50% and 23.83 vs. 1.50%, respectively).

Titratable acidity (TtA), SSC/TtA, and BrY were significantly affected by the interaction between Treatment and Year. As for TtA, significant differences were detected among IRR and RDI in 2020 (0.51 vs. 0.44 g% of citric acid, respectively). No appreciable variation for SSC/TtA was recorded between IRR and RDI in 2019, while the same quality index was improved (+28.73%) by the RDI strategy in the second year of the experiment. The highest value of BrY was observed under RDI in 2019 (7.16 t ha^{-1}), differing from the IRR management in the same year (6.13 t ha^{-1}).

Table 4. Effects of Treatments (IRR = full irrigation, RDI = regulated deficit irrigation), Year (2019–2020), and Treatment × Year interaction on fruit defects, technological traits, and brix yield (cv "Heinz 1534").

	TDF (%)	SsF (%)	CRACK (%)	VrF (%)	pH	TtA (g% CA)	SSC (°Bx)	DM (g%)	SSC/TtA	BrY (t ha^{-1})
Treatment										
IRR	15.00 a	4.25 a	1.88 a	13.00 a	4.44 a	0.48 a	5.32 b	6.40 b	11.02 b	5.27 A
RDI	21.67 a	4.17 a	2.17 a	15.33 a	4.54 a	0.46 a	5.78 a	6.85 a	12.73 a	5.58 A
Year										
2019	5.50 b	2.67 a	1.33 a	1.50 b	4.60 a	0.45 a	5.15 b	5.84 b	11.36 a	6.65 A
2020	31.17 a	5.80 a	2.30 a	24.10 a	4.42 b	0.47 a	5.79 a	7.11 a	12.39 a	4.20 B
Treatment × Year										
IRR × 2019	6.00 a	1.33 a	2.00 a	2.67 a	4.58 a	0.43 b	4.82 a	5.40 a	11.21 ab	6.13 B
RDI × 2019	5.00 a	4.00 a	0.67 a	0.33 a	4.61 a	0.48 ab	5.48 a	6.27 a	11.51 ab	7.16 A
IRR × 2020	24.00 a	6.00 a	1.80 a	19.20 a	4.35 a	0.51 a	5.62 a	7.00 a	10.84 b	4.40 C
RDI × 2020	38.33 a	4.33 a	3.67 a	30.33 a	4.46 a	0.44 b	6.07 a	7.44 a	13.95 a	3.99 C
Significance										
Treatment	ns	ns	ns	ns	ns	ns	*	*	*	ns
Year	***	ns	ns	***	***	ns	**	***	ns	***
Treatment × Year	ns	ns	ns	ns	ns	***	ns	ns	*	**
Mean	18.33	3.92	2.03	13.13	4.50	0.46	5.50	6.53	11.88	5.42

TDF = total defective fruits, SsF = sunscald fruits, CRACK = cracking fruits, VrF = fruits viral symptoms, TtA = titratable acidity, SSC = soluble solids content, DM = fruit dry matter, SSC/TtA = soluble solids content-to-titratable acidity ratio, BrY = brix yield. ns, *, **, *** = non-significant or significant at $p \leq 0.05$, 0.01, and 0.001, respectively. Different letters within each column indicate significant differences between treatments, year, and treatment × year according to Duncan's test ($p \leq 0.05$).

3.5. Carbohydrate and Secondary Metabolites Content

As shown in Table 5, the effect of RDI treatment on tomato fruits did not result in a significant effect on Fru, Suc, and Sta in both years (on average, 9.28, 0.75, and 3.85 mg g^{-1} FW, respectively). RDI determined an increase in Glc of 16.20% and a decrease in the Fru/Glc ratio of 6.67% compared to IRR. Glc and the Fru/Glc ratio were also influenced by the year of treatment. Glucose content was higher in 2020 (+17.20%) than in 2019, while the Fru/Glc ratio decreased by 11.53% compared to 2019. No significant effect was observed regarding the interaction between Treatment × Year. The RDI strategy determined an increase in polyphenols content (+17.50%) compared to IRR. Lyc was only affected by the year factor, which determined a higher content in 2019 than in 2020 (on average, 92.2 and 32.1 µg 100 g^{-1} FW, respectively).

3.6. Protein and Free Amino Acid Contents

The protein content was significantly influenced by the year of cultivation (Table 6). Indeed, in 2019, it was 56.62% higher than in 2020. The year of cultivation also significantly influenced some amino acids. Glutamate (Glu), monoethanolamine (MEA), phenylalanine (Phe), and threonine (Thr) decreased in 2020 (−57.08%, −29.16%, −30.14%, and −44.74%, respectively) compared to 2019. On the contrary, the contents of alanine (Ala), arginine (Arg), glycine (Gly), ornithine (Orn), proline (Pro), and essential amino acids (EAAs) increased in 2020 by 169.05%, 103.39%, 53.85%, 77.78%, 33.33%, and 106.45%, respectively, compared to 2019. Among the EAAs, methionine (Met) content increased by 36.75-fold, ranging from 0.08 to 2.94 µmol g^{-1} FW from 2019 to 2020.

3.7. Principal Component Analysis

A principal component analysis (PCA) was carried out on all assessed data. The first three principal components (PCs) accounted for 100% of the total variance, with PC1, PC2, and PC3 corresponding to 67.3, 21.6, and 11.1%, respectively (Table S2). A biplot was realized for the visualization of PC1 and PC2 (Figure 5). The two years of cultivation were clearly separated on PC1, contributing to the majority of variance (67.3%), whereas the irrigation treatments were separated on PC2, contributing to only 21.6% of the total variance. PC1 was positively correlated to Met, HI, BERY, Gly, EAA, TDF, VrF, DM, Orn, RY, Tyr, and SSC, while it was negatively correlated to TY, NFR, Lyc, MEA, MY, GY, MNR, Asp, Glu, Phe, Asn, BRY, Thr, WY, Prot, and Fru/Glc. PC2, on the other hand, was positively correlated to Ile, Val, BCAA, Gln, Trp, Ser, FRW, Leu, and TTA and negatively correlated to SSC/TtA, Fru, PP, Sucr, Glc, and Pro.

Table 5. Effects of Treatments (IRR = full irrigation, RDI = regulated deficit irrigation), Year (2019–2020), and Treatment × Year interaction on soluble sugars, starch, lycopene, and polyphenols content on tomato fruits (cv "Heinz 1534").

	Glc (mg g^{-1} FW)		Fru (mg g^{-1} FW)		Fru/Glc		Suc (mg g^{-1} FW)		Sta (mg g^{-1} FW)		Lyc (µg 100 g^{-1} FW)		PP (mg GAE 100 g^{-1} FW)	
Treatment														
IRR	11.8	b	8.91	a	0.75	a	0.63	a	3.87	a	64.2	a	39.3	B
RDI	13.9	a	9.65	a	0.70	b	0.87	a	3.82	a	60.2	a	47.4	A
Year														
2019	11.8	b	9.05	a	0.78	a	0.82	a	3.70	a	92.2	a	39.8	A
2020	14.0	a	9.51	a	0.69	b	0.68	a	3.99	a	32.1	b	46.9	A
Treatment × Year														
IRR × 2019	10.7	a	8.68	a	0.81	a	0.64	a	3.86	a	94.7	a	37.6	A
RDI × 2019	12.8	a	9.42	a	0.74	a	1.00	a	3.55	a	89.7	a	41.9	A
IRR × 2020	12.9	a	9.14	a	0.71	a	0.63	a	3.89	a	33.6	a	40.9	A
RDI × 2020	15.1	a	9.89	a	0.66	a	0.74	a	4.10	a	30.6	a	52.8	A
Significance														
Treatment	*		ns		*		ns		ns		ns		*	
Year	*		ns		***		ns		ns		***		ns	
Treatment × Year	ns		ns		ns		ns		ns		ns		ns	
Mean	12.9		9.28		0.73		0.75		3.85		62.16		43.31	

Glc = glucose, Fru = fructose, Fru/Glc = fructose-to-glucose ratio, Suc = sucrose, Sta = starch, PP = polyphenols, Lyc = lycopene. ns, *, **, *** = non-significant or significant at $p \leq 0.05$, 0.01, and 0.001, respectively. Different letters within each column indicate significant differences between treatments, year, and treatment × year according to Duncan's test ($p \leq 0.05$).

Table 6. Effects of Treatments (IRR = full irrigation, RDI = regulated deficit irrigation), Year (2019–2020), and Treatment × Year interaction on proteins (mg g^{-1} FW) and free amino acids (µmol g^{-1} FW) of tomato fruits (cv "Heinz 1534").

	Treatment				Year				Treatment × Year								Significance			Mean
	IRR		RDI		2019		2020		IRR × 2019		RDI × 2019		IRR × 2020		RDI × 2020		T	Y	T × Y	
Prot	1.66	a	1.77	a	2.13	a	1.36	b	1.98	a	2.29	a	1.48	a	1.25	a	ns	*	ns	1.75
Ala	3.05	a	1.91	a	1.26	b	3.39	a	1.01	b	1.51	b	4.27	a	2.31	b	ns	***	*	2.28
Arg	1.14	a	0.75	a	0.59	b	1.20	a	0.60	a	0.57	a	1.45	a	0.92	a	ns	***	ns	0.89
Asn	7.31	a	7.15	a	7.43	a	6.87	a	7.40	a	7.46	a	7.26	a	6.84	a	ns	ns	ns	7.24
Asp	5.18	a	5.04	a	5.52	a	4.60	a	5.59	a	5.46	a	4.93	a	4.63	a	ns	ns	ns	5.15
GABA	9.08	a	7.78	a	7.58	a	8.79	a	8.25	a	6.91	a	9.58	a	8.65	a	ns	ns	ns	8.35
Gln	13.90	a	10.20	a	12.30	a	12.00	a	13.20	a	11.50	a	14.30	a	8.80	a	ns	ns	ns	12.00
Glu	17.90	a	14.50	a	24.00	a	10.30	b	26.60	a	21.40	a	12.60	a	7.61	a	ns	***	ns	17.10
Gly	0.34	a	0.34	a	0.26	b	0.40	a	0.23	a	0.28	a	0.41	a	0.41	a	ns	**	ns	0.33
His	0.99	a	0.94	a	0.97	a	0.92	a	1.01	a	0.94	a	0.98	a	0.94	a	ns	ns	ns	0.97
Met	1.89	a	1.34	a	0.08	b	2.94	a	0.08	a	0.07	a	2.97	a	2.60	a	ns	***	ns	1.43
MEA	0.21	a	0.19	a	0.24	a	0.17	b	0.25	a	0.23	a	0.19	a	0.16	a	ns	*	ns	0.20
Orn	0.15	a	0.11	a	0.09	b	0.16	a	0.10	a	0.09	a	0.18	a	0.14	a	ns	**	ns	0.13
Phe	0.65	a	0.56	a	0.73	a	0.51	b	0.77	a	0.70	a	0.58	a	0.42	a	ns	*	ns	0.62
Pro	0.57	b	0.76	a	0.54	b	0.72	a	0.42	a	0.66	a	0.67	a	0.86	a	*	*	ns	0.65
Ser	1.42	a	1.01	a	1.03	a	1.37	a	0.90	b	1.15	ab	1.74	a	0.88	b	ns	ns	*	1.17
Thr	0.33	a	0.23	a	0.38	a	0.21	b	0.43	a	0.32	a	0.26	a	0.14	a	ns	**	ns	0.29
Tyr	0.89	a	0.70	a	0.61	a	0.92	a	0.68	a	0.55	a	1.02	a	0.85	a	ns	ns	ns	0.77
TAA	57.40	a	46.80	a	57.20	a	48.20	a	60.50	a	54.00	a	55.60	a	39.70	a	ns	ns	ns	52.40
BCAA	1.13	a	0.87	a	0.87	a	1.11	a	0.90	a	0.84	a	1.26	a	0.89	a	ns	ns	ns	0.97
EAA	4.95	a	3.84	a	2.79	b	5.76	a	2.94	a	2.65	a	6.16	a	5.03	a	ns	**	ns	4.20

Prot = proteins, Ala = alanine, Arg = arginine, Asn = asparagine, GABA = γ-aminobutyric acid, Gln = glutamine, Glu = glutamate, Gly = glycine, His = histidine, Met = methionine, MEA = monoethanolamine, Orn = ornithine, Phe = phenylalanine, Pro = proline, Ser = serine, Thr = threonine, Tyr = tyrosine, TAA = total amino acids, BCAA = branched amino acids, EAA = essential amino acids. ns, *, **, *** = non-significant or significant at $p \leq 0.05$, 0.01, and 0.001, respectively. Different letters within each column indicate significant differences between treatments (T), year (Y), and treatment × year (T × Y) according to Duncan's test ($p \leq 0.05$).

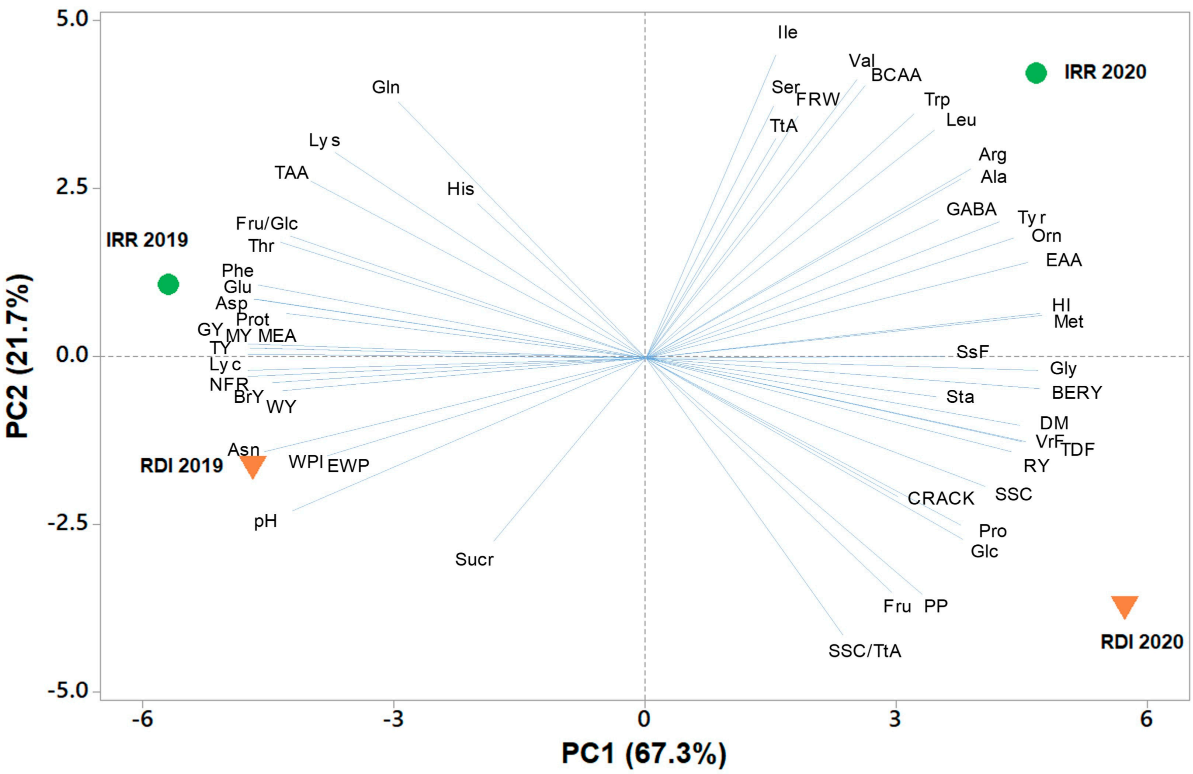


Figure 5. Principal component analysis (PCA) of the analyzed parameters on processing tomato crop subjected to two irrigation treatments (IRR = full irrigation, RDI = regulated deficit irrigation) in the years 2019 and 2020. FRW = average fruit weight, NFR = number of marketable fruits per plant, TY = total yield, MY = marketable yield, WY = unmarketable fruits, RY = rotten fruits, BERY = fruits affected by blossom-end rot, GY = unripe fruits, HI = harvest index, WPI = irrigation water productivity, EWP = economic water productivity, TDF = total defective fruits, SsF = sunscald fruits, CRACK = cracking fruits, VrF = viral fruit symptoms, pH, TtA = titratable acidity, SSC = soluble solids content, DM = fruit dry matter, SSC/TtA = soluble solids content-to-titratable acidity ratio, BrY = brix yield, Glc = glucose, Fru = fructose, Fru/Glc = fructose-to-glucose ratio, Suc = sucrose, Sta = starch, PP = polyphenols, Lyc = lycopene, Prot = proteins, Ala = alanine, Arg = arginine, Asn = asparagine, Asp = aspartic acid, GABA = γ-aminobutyric acid, Gln = glutamine, Glu = glutamate, Gly = glycine, His = histidine, Ile = isoleucine, Leu = leucine, Lys = lysine, Met = methionine, MEA = monoethanolamine, Orn = ornithine, Phe = phenilalanine, Pro = proline, Ser = serine, Thr = threonine, Trp = tryptophan, Tyr = tyrosine, Val = valine, TAA = total amino acids, BCAA = branched amino acids, EAA = essential amino acids.

4. Discussion

4.1. Effect of Irrigation Management on Crop Growth, Yield, Sustainability, and Fruit Defects

Although the meteorological conditions were similar across the two growing seasons (Table S3), the effect of the year of cultivation was evident in most of the evaluated traits regarding yield and fruit defects. In 2020, early infections by *Fusarium* spp. (a fungi causing tracheomycotic disease) and Tomato Spotted Wilt *Orthotospovirus* (TSWV) were observed on tomato plants, as reported by Fusco et al. (2023) [32]. The combined attack by TSWV and *Fusarium* spp. affected both VDB and FDB traits throughout the whole crop cycle, reducing by 56.74%, on average, the total aboveground biomass at harvest with respect to 2019. A relevant leaffall was also noted, as confirmed by the greater harvest index observed in 2020. Therefore, the low productivity assessed in 2020 led to a substantial drop in WP_I and EWP compared to 2019. In the final part of the crop cycle (from 8 August to harvesting, lasting 26 days), higher SWD was observed in RDI, which may have negatively affected FRW in comparison with the IRR strategy. Indeed, the decreased soil water content during fruit ripening in RDI may have caused a water backflow to the plant through the xylem (internal water deficit between crop evapotranspiration and root absorption) and a subsequent loss in fruit size [42,43].

Interestingly, despite the effect of the Year factor, the remarkable reduction of irrigation volumes induced by RDI with respect to the IRR strategy (corresponding to water savings of 21.14% in 2019 and 18.79% in 2020) did not significantly affect total yield and its components. Several studies applying a regulated water deficit strategy (50% ET_c restoration) at different phenological stages have been performed in the last twenty years. Under Southern Italy conditions, Patanè and Cosentino (2010) [17] and Patanè et al. (2011) [7] applied the RDI strategy at a more sensitive phenological phase (beginning of flowering) [44]. RDI did not affect total, marketable, or brix yields or fruit size of the 'Brigade' cultivar at both experimental sites of Southern Italy, while SSC, TtA, and ascorbic acid were enhanced with respect to the full irrigation strategy. Favati et al. (2009) [12] and Lovelli et al. (2017) [31] induced the reduction of irrigation volumes at the beginning of the ripening process (breaker stage) in another field trial in Southern Italy (Basilicata region). Favati et al. (2009) [12] obtained similar results to the previously mentioned research on the 'Ability' cultivar, and RDI was found to boost carotenoid (lycopene and β-carotene) contents compared to IRR. Other investigations were carried out in Spain (Extremadura and Navarra regions) by applying RDI management starting from fruit development [18,45]. Valcarcel et al. (2020) [18] recorded a significant effect of the interaction among genotype and RDI treatment on marketable yield in four processing tomato cultivars ('H-9661', 'H-9997', 'H-9036', 'ISI-24424'), while no effect of RDI was observed in the same varieties by Campillo et al. (2017) [45]. In agreement with the abovementioned literature, in our study, no significant variations were observed in yield and its components as an effect of RDI in comparison with the full irrigation strategy (100% ETc restoration). Additionally, HI and the incidence of defects on ripe fruits were not affected by irrigation management, according to previous research [31,46]. The RDI strategy significantly increased the environmental and economic sustainability of the processing tomato crop. Indeed, WP_I and EWP indexes were improved by RDI, in agreement with the findings reported by Patanè et al. (2011) and Favati et al. (2009) [7,12], although WP_I was affected by the T × Y interaction. WP_I stands for the kilograms of marketable tomato produced per unit of irrigation water (m^3) supplied to the crop [34], while EWP focuses on the economic viability of agronomic management [35]. Thus, RDI applied at the BBCH 701 phenological stage (relative to Solanaceous fruits, when the first fruit cluster has reached the typical size) may economically and environmentally benefit processing tomato farmers, especially in drought-prone areas such as the Capitanata district. Notwithstanding the enhanced sustainability induced by RDI management, it is worth noting that its effects may vary based on the soil texture [29].

4.2. Effect of Irrigation Management on Technological Traits and Reducing Sugars

The profitability of the processing tomato crop depends not only on yield but also on some technological attributes. In our experiment, SSC and DM were enhanced in RDI-treated tomatoes compared to IRR-treated ones, in agreement with extensive reviews [42,43,47]. Higher DM levels resulted in lower fruit perishability during the transport phase and optimized processing efficiency (i.e., higher paste yield). Soluble solids content (SSC) is commonly measured as it is strongly correlated with DM content, and values above 4.5 °Bx are recommended by tomato industries [48]. SSC and DM were also higher in 2020 compared to 2019 due to an additional reduction of irrigation volumes, which may have been due to extreme effects of three-week-late transplanting (i.e., higher temperatures in the last phase of cultivation). Indeed, Gautier et al. (2008) [49] observed that higher temperatures during fruit ripening increase canopy transpiration, thus promoting sugar accumulation. With respect to DM and SSC, an inverse pattern (both among years and between treatments) was observed for the fructose-to-glucose ratio, which is an important index of fruit sweetness [49]. Usually, cultivated tomato fruits show equimolar concentrations of glucose and fructose since both are derived from the hydrolysis of exported sucrose.

However, fructose is perceived to be almost twice as sweet as glucose and, therefore, tomato cultivars with enhanced Fru/Glc ratios (enhanced sweetness and taste) are preferentially selected [49]. The variations in Fru/Glc depended on a significant increase in glucose in 2020 compared to 2019 and on RDI treatment rather than IRR, while fructose remained unchanged. Processing tomato plants may thus have responded to abiotic and biotic stresses by varying the sucrose concentration difference between phloem and sink and stimulating sugar (glucose) accumulation in fruits [43]. Glucose is recognized and/or activates hexokinase 1 (HXK1), an enzyme with both catalytic and sensory activity [50]. In response to an increase in glucose levels, HXK1 functions as a positive regulator of plant immune responses, particularly those related to pathogen-associated molecular patterns (PAMPs). The latter induces the accumulation of pathogenesis response (PR) proteins [51]. However, the apparently reduced sweetness perception may have been mitigated by the improved SSC/TtA ratio in RDI with respect to IRR management observed in 2020. SSC/TtA is commonly used as an index of tomato taste and quality for fresh and canned tomatoes [47]. In sensorial tests, tomatoes with higher values of SSC/TtA had a sweeter taste and better flavor ratings and garnered an overall preference when compared to the ones with a lower ratio since higher citric acid concentrations enhance glucose sweetness perception [52]. Regarding pH, an important technological trait preserving processed tomato products against spoilage of thermophilic microorganisms [48], it was found to be lower in 2020 compared to 2019 due to reduced water availability, according to Valcárcel et al. (2020) [18].

4.3. Effect of Irrigation Management on Lycopene, Polyphenols, and Amino Acids

No significant interaction between Treatment and Year was observed for all analyzed metabolites, except for the amino acids alanine and serine. This is extremely interesting because the concomitant increase or decrease of these two metabolites has been already observed in tomatoes [53]. Usually, a serine increase may be related to a decrease in transpiration and an enhancement of the rate of photorespiration, as previously found by Salvioli et al. (2012) [23]. However, in 2020, RDI treatment resulted in significant SWD, and the serine content was lower than in IRR. *Fusarium* spp. infections may have enhanced stomatal conductance and transpiration in plants under water stress, making them more prone to infection, as previously seen in *Vicia faba* leaves infected by *Sclerotinia sclerotiorum* [54]. In fact, *S. sclerotiorum* deregulates guard cells during infection through a cellular response dependent on oxalic acid, which acts as a virulence factor, altering the organic solutes content in guard cells. This effect has also been observed in other infected plants, as reported by Lindenthal et al. (2004) [55]. It is likely that when leaves wilt, plants may trigger mechanisms to redistribute their nutrients, enriching the phloem sap with sugars, amino acids, organic acids, and minerals that could be easily acquired by the pathogen. However, at the same time, these nutrients may be more easily translocated to the growing fruits accelerating the tomato crop cycle, which, accordingly, was shorter in 2020 compared to 2019. The decrease in alanine, simultaneously with that of serine, in the RDI 2020 treatment could depend on its anaplerotic use for producing pyruvate to support the TCA cycle and provide carbon skeletons and ATP for the growth and premature ripening of fruits.

The polyphenols content was higher with RDI treatment, and it did not decrease under pathogen infection in 2020, as also previously found by Abdelaziz et al. (2022) in tomato plants affected by *Fusarium* wilt [56]. These metabolites, which increase in tomatoes under a water deficit, as previously found by Patanè et al. in 2021 and Jin et al. in 2022 [57–59], have high ROS scavenger activity and a strong capacity to protect the membrane and protein structures, conferring plants resistance both to drought stress and pathogens. Moreover, in foods, they are more effective antioxidants than vitamins due to their capacity to take part in redox reactions transporting protons and electrons [57]. Interestingly, lycopene content did not vary with irrigation management. Martí et al. (2018) observed that Lyc was more influenced by genotype, site, and year of cultivation than irrigation dose [19]. Accordingly, Lyc was significantly decreased in 2020, plausibly by *Fusarium* spp. and TSWV infections, as previously seen by Adisa et al. (2020) [60], independently of irrigation treatment. The defense response to pathogens shifts the metabolic pathways away from lycopene synthesis due to its high biosynthetic cost, prioritizing the production of recyclable metabolites like GABA and proline. GABA and proline may act both as compatible osmolytes to balance the decrease in water potential during drought stress and/or ROS scavengers for stabilizing and protecting membranes and macromolecules under the pathogenic attack from TSVW and *Fusarium* spp. [61]. Accordingly, the activity of enzymes involved in proline biosynthesis, such as ornithine aminotransferase (OAT), glutamate dehydrogenase (GDH), and Δ1-pyrroline-5-carboxylate synthetase (P5CS), is increased in *Vigna mungo* cultivars in response to yellow mosaic virus (YMV) infection as a part of an induced defense response [62]. Similarly, GABA is accumulated during fungal infections to regulate the hypersensitive response and bolster the plant's resistance against fungal pathogens by anaplerotically maintaining the TCA cycle while mitigating oxidative damage [63]. Indeed, the increase in the proline content of tomato fruits recorded in 2020 can also certainly be related to drought stress, as found previously by Singh Gujjar et al. [64]. In fact, this amino acid, beyond its role as an osmolyte, can detoxify ROS, maintain cellular redox balance, protect macromolecules and membranes, and induce the expression of stress-responsive genes containing proline-responsive elements (e.g., PRE, ACTCAT) [65].

5. Conclusions

The present study revealed that RDI holds the potential to enhance both the environmental and the economic sustainability of the processing tomato crop. While crop yield was maintained comparable to full irrigation management, RDI enhanced SSC and DM traits, which are appreciated by canning industries, thus potentially allowing farmers to reach even higher profits. Some level of tolerance to prolonged deficit irrigation in the reproductive phases of the processing tomato crop may be attributed to the high contents of proline, polyphenols, and GABA as drought stress metabolite markers in fully ripe fruits. Their presence offers a dual advantage, serving both as a plant defense mechanism and as food functional metabolites. It is worth noting that, notwithstanding its approval as a food additive in several countries (e.g., Japan, EU, and USA), the beneficial role of GABA remains largely unknown, mainly for the low contents in agricultural products. Indeed, it has been proven to prevent type 1 diabetes, immunological disorders, neural diseases, asthma, and cancer. Consequently, the high GABA content observed in processing tomatoes highly contributes to enhancing the fruit quality of produce, together with the higher glucose and soluble solids contents and fruit dry matter. Finally, applying the RDI strategy in the BBCH 701 phenological stage (relative to Solanaceous fruits, when the first fruit cluster has reached the typical size) represents a valuable compromise to maintain yield and boost fruit quality by saving over 20% of the seasonal irrigation volume in a semi-arid Mediterranean environment. It is worth noting that, in the near future, applying a deficit irrigation strategy may lead to environmental certifications favoring consumers' preferences and resulting in additional economic benefits. However, since a great variability in RDI efficiency has been observed across the Mediterranean area based on soil texture and genotypes, future research should focus on strengthening RDI's water-saving power by complementing it with other techniques such as biodegradable mulching.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su16093798/s1: Table S1: Agronomic management of the open-field trial and soil characteristics; Table S2: Eigenvalue, relative and cumulative proportion of total variance, and correlation coefficients for all data about the processing tomato crop subjected to two irrigation treatments (IRR = full irrigation, RDI = regulated deficit irrigation) in the years 2019 and 2020 with respect to the three principal components; Table S3: Comparison between monthly average temperatures and rainfall totals from 2019 to 2020 and long-term historical data (1951–2018).

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A.B. and P.C. (Petronia Carillo); validation, M.P., P.C. (Petronia Carillo), D.R. and P.C. (Pasquale Campi); formal analysis, A.B., G.M.F., A.P., R.N., A.F.M. and D.R.; investigation, G.M.F., A.P., R.N., A.F.M., F.S.d.C., M.P. and P.C. (Pasquale Campi); resources, M.P.; data curation, M.P., P.C. (Petronia Carillo), P.C. (Pasquale Campi) and D.R., writing—original draft preparation, A.B., G.M.F., M.P., P.C. (Petronia Carillo) and P.C. (Pasquale Campi); writing—review and editing, A.B., G.M.F., M.P., P.C. (Petronia Carillo), P.C. (Pasquale Campi) and D.R.; visualization, A.B., P.C. (Petronia Carillo) and P.C. (Pasquale Campi); supervision, M.P.; project administration, M.P.; funding acquisition, M.P. All authors have read and agreed to the published version of the manuscript.

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