applied sciences

MDPI

Article

Irrigation Scheduling in Processing Tomato to Save Water: A Smart Approach Combining Plant and Soil Monitoring

Federica Carucci [1], Anna Gagliardi [2], Marcella Michela Giuliani [2,*] and Giuseppe Gatta [2]

[1] Department of Agricultural and Forestry Sciences (DAFNE), University of Tuscia, 01100 Viterbo, Italy; federica.carucci@unitus.it

[2] Department of Agricultural Sciences, Food, Natural Resources and Engineering (DAFNE), University of Foggia, 71122 Foggia, Italy; anna.gagliardi@unifg.it (A.G.); giuseppe.gatta@unifg.it (G.G.)

* Correspondence: marcella.giuliani@unifg.it; Tel.: +39-3204394685

Abstract: The gradual reduction of water reserves for irrigation has become a worldwide concern. To improve the irrigation of processing tomato, we conducted a study to evaluate a system that monitors both plant water status and soil moisture levels (PlaSoMan) compared to an evapotraspirometric method (IrriMan) and an empirical farmer's management (FarMan) in a two-year field trial. The results showed that PlaSoMan saved around 30% and 7.5% of water, with a yield loss of only 10% and 2.5% compared to FarMan and IrriMan, respectively. Thus, PlaSoMan showed satisfactory irrigation water use efficiency (IWUE) over the two years. Moreover, IrriMan and PlaSoMan had lower blue water requirement (BWR) values than FarMan. Finally, PlaSoMan reached the highest value of the yield quality indicator, which combined total yield and brix degree. Thus, the new system, which assesses both plant water status and soil moisture levels, appears to be associated with high-quality and water-friendly tomato production representing an efficient solution for areas with limited water resources.

Keywords: water saving; irrigation scheduling; water use efficiency; blue water requirement; wireless sensors; yield quality; plant water status; soil moisture level; smart irrigation

Citation: Carucci, F.; Gagliardi, A.; Giuliani, M.M.; Gatta, G. Irrigation Scheduling in Processing Tomato to Save Water: A Smart Approach Combining Plant and Soil Monitoring. *Appl. Sci.* **2023**, *13*, 7625. https://doi.org/10.3390/app13137625

Academic Editor: José Miguel Molina Martínez

Received: 29 May 2023
Revised: 21 June 2023
Accepted: 26 June 2023
Published: 28 June 2023

1. Introduction

Processing tomato (*Solanum lycopersicum* L.) is a globally important crop, with a worldwide production estimated at 39 million tons in 2021 [1]. Size, form, color, fruits' dry matter and soluble solids contents are important quality parameters for the processing industry [2]. Furthermore, tomatoes are rich in lycopene, carotenoids, flavonoids, vitamin C, K1, B2, B9, potassium, copper, iron, and phosphorous. For this reason, it has been considered a functional food, which means that its regular consumption may prevent and/or act on certain human diseases [3]. Tomato has a high input and water-intensive growing system, particularly for its high water-demanding: 400–600 mm of irrigation water, rising due to ongoing climate change [4]. However, in recent years, we have witnessed a gradual reduction of water reserves for irrigation in quantity and quality [5]. Among the many causes, it is possible to include ongoing climate change, increased demand for civil and industrial uses, and incorrect irrigation application with consequent waste. Therefore, improving irrigation water use efficiency (IWUE) is one of the major agricultural challenges that modern technologies are helping to resolve [6]. Furthermore, improved IWUE helps achieve sustainability in water use and contributes to increasing agricultural production's competitiveness [7]. In response to global water scarcity, blue water requirement (BWR) can be a useful index. BWR estimates the irrigation consumption per product unit and is particularly interesting with crops that require significant amounts of water that cannot be fulfilled by the scarce rainfall during the crop cycle, and for which, irrigation is crucial [8]. Given these premises, the identification of technological innovations that make it possible to rationalize and optimize irrigation water use appears of great interest. Irrigation scheduling represents a decision-making process that seeks to provide plants with appropriate quantities of water at appropriate times. Despite some on-farm system irrigation schedules are now available, mainly based on soil water balance, the common irrigation scheduling in use in tomato growing systems is still based on fixed intervals between irrigation supplies without considering the actual crop water demand [9], leading to over-irrigation and poor IWUE [10]. Furthermore, to the best of our knowledge, none of the existing irrigation scheduling systems currently incorporate monitoring of both plant water status and soil moisture level. Thus, to optimize the irrigation of processing tomatoes, the aims of this research were: (1) to implement a smart system based on monitoring of both plant water status and soil moisture level, based on the use of wireless sensors; and (2) to compare the smart system with an approach based on evapotraspirometric model and an empiric approach managed by the farmer.

2. Materials and Methods

2.1. Agronomic Trials

We conducted field experiments in Southern Italy (41°24′27′′ N; 15°45′34′′ E, 30 m above sea level) during the 2015 and 2016 crop seasons. We cultivated the Ulisse processing tomato cv. from Syngenta Seeds SpA with elongated fruits using three irrigation scheduling methods described in Section 2.2. We arranged the experiments in a strip-plot design with four replicates, and each experimental unit covered a surface area of 2500 m^2. We transplanted the tomato seedlings on 10 May 2015 and 26 May 2016, in paired rows spaced at 1.8 m apart. The distance between the paired rows and the plants within the rows was 0.5 m and 0.4 m, respectively. The plant density was 2.7 plants per square meter. Before transplanting, we took soil samples (0–0.4 m depth) to assess their physical characteristics, as outlined in Table 1. We followed standard agricultural practices during both crop seasons, including basic fertilization using 72 kg ha^{-1} N and 128 kg ha^{-1} P, and adding 82 kg ha^{-1} N by fertigation during the crop cycle. We also performed pest and weed control using current management practices.

Table 1. Main physical parameters of the soil detected in the two growing seasons.

Parameter	2015	2016
Sand (% dry weight)	21.5	25.5
Silt (% dry weight)	47.0	45.5
Clay (% dry weight)	31.5	29.4
Apparent Bulk Density (kg/dm^3)	1.2	1.2
Field Water Capacity (% dry weight)	33.2	34.6
Wilting Point (% dry weight)	18.8	19.0
Available Water (% dry weight)	14.4	15.7-

In relation to irrigation, three independent irrigation sectors were set up at the beginning of the two crop cycles. Each sector was equipped with a drip irrigation system, as a single plastic pipe arranged in the middle of each paired row, with drippers of 2 L h^{-1} flow rate spaced every 0.2 m. Volumetric flow meters were used to monitor the volumes distributed for each irrigation scheduling method. The seasonal irrigation volumes and the number of irrigations referred to the three irrigation scheduling methods modes in the two growing seasons are reported in Table 2. The crop was hand harvested when the ripe fruit rate reached about 95% (1 September 2015; 14 September 2016) on a test area of 30 m^2 in each replicate.

Table 2. Seasonal irrigation volumes, rainfall, total volumes, and number of irrigations applied in the 2015 and 2016 growing seasons for the three irrigation scheduling methods under study.

	Irrigation Scheduling Methods *					
	FarMan		**IrriMan**		**PlaSoMan**	
	2015	**2016**	**2015**	**2016**	**2015**	**2016**
Irrigation volumes (m^3/ha)	6200	6075	5070	4174	4570	4000
Rainfall (mm)	118	197	118	197	118	197
Total volumes (m^3/ha)	7380	8045	6250	6144	5740	5970
Irrigation events (n)	36	34	31	28	26	23
Average irrigation interval (d)	3.1	3.3	3.6	4	4.3	4.8
Average irrigation volume (m^3/ha)	172.2	178.7	163.5	149.2	175.7	173.9

* FarMan: irrigation scheduling managed by the farmer. IrriMan: irrigation scheduling based on "Irriframe" model. PlaSoMan: irrigation scheduling based on the smart system that monitors both plant water content and soil moisture.

Throughout the experimental period, a nearby weather station recorded the daily measurements of rainfall (mm) and maximum and minimum air temperature (°C) in proximity to the experimental fields (Figure 1). The two growing seasons exhibited distinct rainfall patterns, with only 118 mm of rainfall in 2015 compared to 197 mm in 2016.

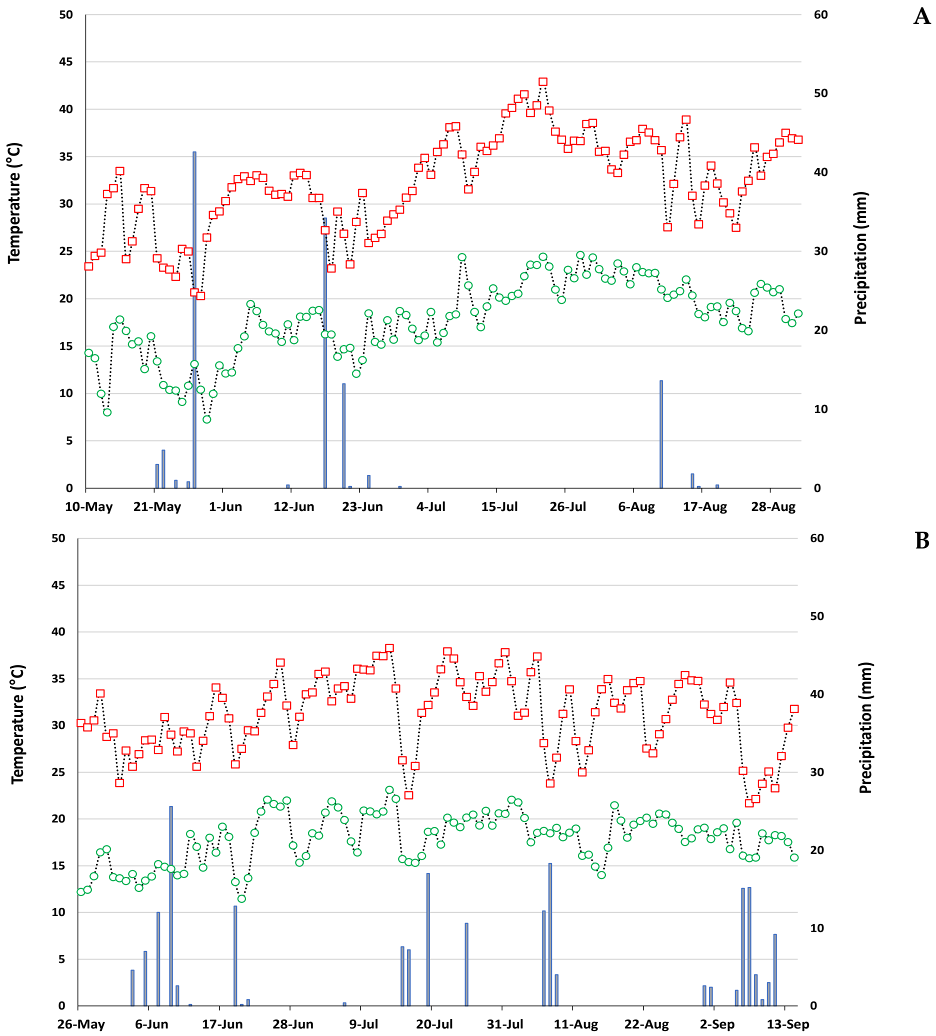

Figure 1. Rainfall (blue histograms), maximum (red points) and minimum (green points) daily temperatures, recorded during the two processing tomato growing seasons ((**A**) 2015 and (**B**) 2016).

2.2. Irrigation Scheduling Management

2.2.1. Irrigation Scheduling Managed by the Farmer (FarMan)

This study is part of the "Use of Innovative Systems based on Wireless Sensor Networks in the Irrigation Planning of Tomato Processing" project (SIWIP), funded by the Italian Ministry of Agricultural, Food and Forestry Policies. The research was conducted in collaboration with a farm that has a longstanding association with processing tomato production and is part of a producer organization that manages around 500 hectares of processing tomatoes. According to the technique commonly used in the area, the farmer used fixed intervals (from 2 to 6 days) for irrigation in an attempt to reduce the water stress of the crops and make irrigation management easier [9]. However, this technique failed to consider the soil water content or the crop's water requirements and can be considered an empiric method. The total irrigation volumes applied by the farmer during the two tomato crop cycles and the number of irrigation events are reported in Table 2.

2.2.2. Irrigation Scheduling Based on Irriframe Model (IrriMan)

The approach used for irrigation scheduling was based on the "Irriframe" platform developed by the Water Boards Italian Association [11]. This model takes into account the soil, plant, and atmosphere continuum, and calculates the crop water requirement using evaporimetric data. The crop coefficients (Kc) [12,13] are adjusted based on local information. The input data include the type of crop, geographic location, meteorological and soil data, and the characteristics of the irrigation system used. The system provides information on expected crop evapotranspiration, the next irrigation date, and the amount of water to be distributed. It offers real-time irrigation scheduling, giving daily guidance on how much and when to irrigate crops. Users can fully interact with the system through the web interface [14].

2.2.3. Irrigation Scheduling Based on the Monitoring of Plant and Soil Water Content (PlaSoMan)

A smart irrigation water system was utilized based on the monitoring of plant water status and moisture soil level, as shown in Figure 2. The first step involves the evaluation of the water status of the plant through the determination of the CWSI (Crop Water Stress Index). To this end, three infrared temperature sensors (Melexis Technologies NV, Belgium) were used to detect the canopy temperature and placed in three representative areas of the field. Each infrared temperature sensor was positioned parallel to the plant rows 0.5 m above the canopy, pointed at 45° toward the tomato rows, and the canopy temperature was recorded every 15 min. The weather station placed next to the experimental field measured relative humidity, air temperature, solar radiation, wind speed, and precipitation every 15 min. All variables were measured at 2 m height. Crop temperature, together with the air temperature and humidity values, were used by the system to calculate CWSI as follows [15]:

$$\mathrm{CWSI} = \frac{(\mathrm{T_c} - \mathrm{T_a}) - (\mathrm{T_c} - \mathrm{T_a})_{\mathrm{LB}}}{(\mathrm{T_c} - \mathrm{T_a})_{\mathrm{UB}} - (\mathrm{T_c} - \mathrm{T_a})_{\mathrm{LB}}}$$

where T_c is the canopy temperature (°C); T_a is the air temperature (°C); $(T_c - T_a)_{LB}$ term corresponds to non-water-stressed baseline (lower baseline), and $(T_c - T_a)_{UB}$ term corresponds to stressed crop condition (upper baseline). Both lower baseline and upper baseline were estimated using the following two empirical equations [15]:

$$(\mathrm{T_c} - \mathrm{T_a})_{\mathrm{LB}} = \mathrm{A} + \mathrm{B} \times \mathrm{VPD}\ \text{(lower baseline)}$$

$$(\mathrm{T_c} - \mathrm{T_a})_{\mathrm{UB}} = \mathrm{A} + \mathrm{B} \times \mathrm{VPG}\ \text{(upper baseline)}$$

where VPD (kPa) is the vapor pressure deficit assuming leaf temperature equal to air temperature; A is the intercept and B is the slope of the linear regression of $(Tc - Ta)_{LB}$

against VPD. In our experimental conditions, A was equal to 1.54 °C and B was equal to −1.95 °C kPa^{-1}. VPG (kPa) is the difference between the saturation vapor pressure evaluated at Ta and air temperature plus the intercept (Ta + A). VPD and VPG were calculated using Ta and RH [16].

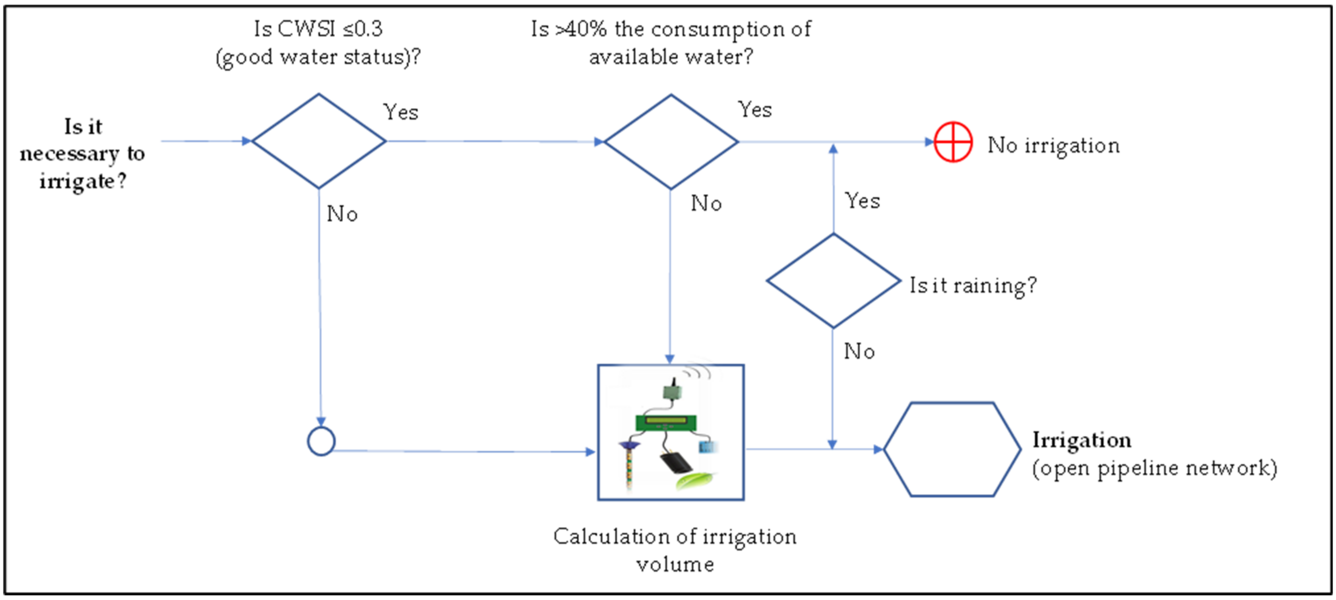

Figure 2. Flowchart of the smart irrigation water system (PlaSoMan) based on the monitoring of plant water status (CWSI) and moisture soil level.

The CWSI values range between 0 (optimal crop water status) and 1 (high crop water stress). The CWSI threshold to start irrigation has been fixed at a value equal to or higher than 0.3 [17]. At this threshold, the system evaluates the soil water content to calculate the irrigation volume to apply to the crop. To make this, frequency domain reflectometry (FDR) sensors were placed at four soil depths (0.15, 0.3, 0.45 and 0.6 m) in the same three representative areas used for leaf temperature monitoring. The soil moisture data were stored and processed by the software. The software also considers the soil hydrological value of field capacity (Table 1) and it can calculate the required irrigation volume to bring the soil to its field capacity value.

The new system conducts a soil water content check even when the CWSI is below 0.3 (good plant water status). If the soil moisture value falls below the fixed threshold of 40% of the available water depletion, the necessary irrigation volume is calculated to bring the soil to its field capacity value. Thus, irrigation started every time the CWSI was equal to or higher than 0.3, or whenever the soil moisture was equal or lower than the fixed threshold. This double-checking of plant water status and soil moisture level represents the innovativeness of the system as it allows irrigation to start even in situations of crop water stress regardless of the soil water conditions. Finally, the system also had rain sensors that could pause irrigation when it rained heavily and resume it when the rainfall was not enough to restore field capacity on its own.

2.3. Yield, Yield Quality Indicator, Water Productivity, and Main Quality Parameters

At harvest, the marketable and discarded fruit were counted and weighted to estimate the total and marketable yield (t ha^{-1}). Moreover, the synthetic yield quality indicator of tomato production (Yield Quality, YQ, t ha^{-1}) was calculated as reported by Giuliani et al., 2019 [4]. A revised water productivity indicator (WP_{YQ}) was then computed considering the ratio between the YQ indicator and total water applied to the crop (irrigation and precipitation) [4].

The quality parameters were evaluated on a sample of 10 marketable fruits from each plot. The soluble solids (°Brix) were measured with a digital refractometer (model DBR35, XS Instruments; Giorgio Bormac s.r.l., Carpi (MO), Italy). Titratable acidity (TA; g citric acid 100 mL^{-1} fresh juice) and pH were measured according to AOAC, (1995 [18]). The color parameters were measured using a CM-700d spectrophotometer (Minolta Camera Co. Ltd., Osaka, Japan) as the CIELAB coordinates (i.e., L*, a*, b*) on four randomly selected areas of the fruit surface. Then, the a*/b*ratio was calculated, which represents an index that describes well the color changes of tomato fruit [19,20].

Lycopene, vitamin C, and beta-carotene content were determined following the procedure described in Ishiwu et al. (2014) [21] on tomato pulp (1 g), obtained using a blender at 12,000 rpm for 10 min.

To determine the lycopene content, we macerated the tomato pulp with a 1% metaphosphoric acid solution and then filtered it. We also used 10 mL of metaphosphoric acid solution to wash off any residue. The resulting residue was then macerated with 20 mL of acetone, filtered, and the absorbance of the filtrate was read at 440 nm against acetone as a blank using a spectrophotometer. We repeated this analysis three times and calculated the mean. Finally, we determined the concentration of lycopene as [21]:

$$\text{Lycopene}\left[\frac{\text{mg}}{100\text{ mL}}\right] = \frac{\text{Mean absorbance} \times \text{dilution factor}}{\text{Slope}}$$

To obtain the concentration of lycopene, we used a slope of 0.095 calculated from the standard curve of lycopene.

To determine the vitamin C content, we macerated 1 g of tomato pulp with 20 mL of 0.4% oxalic acid solution and filtered it. Next, we added 0.2 mL of 0.01% methylene blue solution to 1 mL of filtrate in a test tube. We also added 1 mL of acetate buffer pH 4.2 and made the solution up to the 5 mL mark using distilled water. The spectrophotometer was used to read the absorbance of the solution and vitamin C was calculated as [21]:

$$\text{Vitamin C}\left[\frac{\text{mg}}{100\text{ mL}}\right] = \frac{\text{Mean absorbance} \times \text{dilution factor}}{\text{Slope}}$$

We calculated the slope (0.0693) from the standard curve of vitamin C using known concentrations of vitamin C against absorbance.

To determine the β-carotene content, 1 g of tomato pulp was mixed with a 10 mL combination of acetone and n-hexane (1:1) and filtered. Next, 10 mL of 50% $(NH_4)_2SO_4$ solution was added and vigorously shaken before allowing it to settle. The upper layer was then collected, and the spectrophotometer was used to read the absorbance at 450 nm against hexane as a blank [21]:

$$\text{Beta} - \text{carotene}\left[\frac{\text{mg}}{100\text{ mL}}\right] = \frac{\text{Mean absorbance} \times \text{diluition factor}}{\text{Slope}}$$

The slope (1.249) was obtained from the standard curve of beta-carotene plotted using a known concentration of beta-carotene against absorbance.

2.4. Water Use Efficiency and Blue Water Requirement

At the crop level, the irrigation water use efficiency was calculated (IWUE, t m^{-3}) as the ratio between the marketable yield and the irrigation volume received by the crop [7]. The blue water requirement (m^3 t^{-1}) was calculated by dividing the total irrigation volume by the total crop yield [8].

2.5. Statistical Analysis

We analyzed the dataset by testing it based on the standard assumptions of analysis of variance (ANOVA). To ensure the validity of our results, we performed Shapiro–Wilk and Bartlett's tests to determine the normal distribution and common variance of the experimental error, respectively. We also applied Box–Cox transformations prior to analysis when necessary [22]. Our ANOVA procedure followed a strip-plot design with four replicates, considering the scheduling irrigation method and the growing season as fixed. To determine the statistical significance of the means, we utilized Tukey's honest significance difference post hoc test at the 0.05 significance level.

For a more comprehensive evaluation, we adopted a multivariate approach and statistically processed the different parameters together for principal component analysis (PCA). We standardized the values of each parameter before performing the PCA. We also conducted a factorial analysis on the PCA values, using the varimax method to determine the necessary number of factors based on eigenvalues and the percentage of total variance accounted for by each factor. All analyses were performed using the JMP software package, version 16.2 (SAS Institute Inc., Cary, NC, USA).

3. Results

Table 3 presents the impact of the three irrigation scheduling methods on marketable yield, yield quality indicator, and water productivity for yield quality. FarMan scheduling demonstrated the highest marketable yield. IrriMan and PlaSoMan had comparable yields, but PlaSoMan resulted in a 10% yield loss compared to FarMan, while IrriMan caused a loss of about 7.5%.

Table 3. Effects of the irrigation scheduling method on marketable yield, yield quality indicator (YQ), and water productivity for yield quality (WP_{YQ}).

Parameter	Irrigation Scheduling Method *		
	FarMan	IrriMan	PlaSoMan
Marketable yield (t ha^{-1})	95.8 ± 1.5 ^{a}	88.6 ± 1.4 ^{b}	86.5 ± 1.6 ^{b}
YQ (t ha^{-1})	76.5 ± 1.3 ^{b}	78.7 ± 4.0 ^{b}	87.2 ± 1.8 ^{a}
WP_{YQ} (t m^{-3})	9.9 ± 0.3 ^{c}	12.7 ± 0.6 ^{b}	14.9 ± 0.3 ^{a}

* FarMan: irrigation scheduling managed by the farmer. IrriMan: irrigation scheduling based on "Irriframe" model. PlaSoMan: irrigation scheduling based on the smart system that monitors both plant water content and soil moisture. Tukey HSD significant differences ($p < 0.05$) are indicated by different letters. Data are reported as means ± standard errors (n = 8).

Moreover, PlaSoMan showed the highest values of YQ and WP_{YQ}. Both these parameters showed a significant interaction year x irrigation scheduling method (Figure 3A,B). Only PlaSoMan showed the highest value for both the YQ and WP in both years, even if they were different in terms of rainfall, while, in the second wetter year, the IrriMan scheduling showed the lowest YQ values (Figure 3A) and FarMan the lowest WP_{YQ} values (Figure 3B).

As for the water use efficiency calculated on a marketable yield basis (IWUE), the lowest values were obtained for the FarMan scheduling, which did not show significant differences between the two years. The irrigation scheduling based on the Irriframe model and the new PaSoMan system showed higher IWUE values, especially in 2016 (Figure 4A). Finally, the blue water requirement (BWR) was lower under IrriMan and PlaSoMan, especially in 2016 (Figure 4B).

Moreover, the PlaSoMan showed also the highest values of all the qualitative parameters considered, and FarMan the lowest for soluble solids content, color index, lycopene and β-carotene (Table 4). On the contrary, titratable acidity and pH did not show significant differences among the three irrigation methods investigated (Table 4).

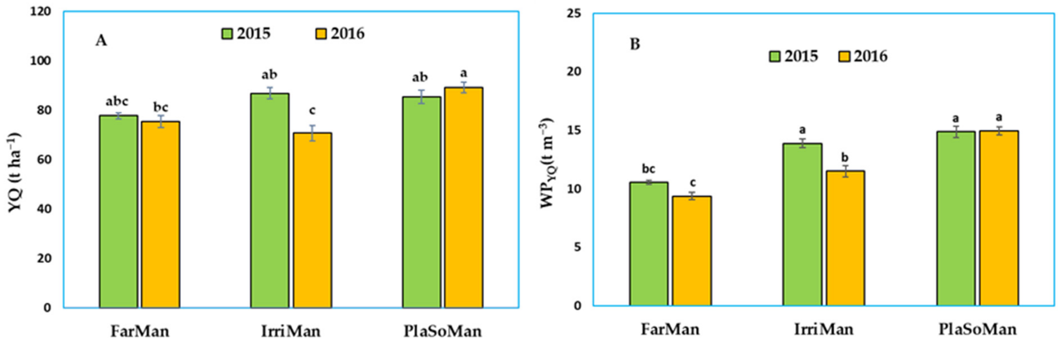

Figure 3. Effect of the interaction year × irrigation scheduling method on yield quality indicator (**A**) and water productivity for yield quality (**B**). Tukey HSD significant differences ($p < 0.05$) are indicated by different letters. Vertical bars indicate standard errors (n = 4). FarMan: irrigation scheduling managed by the farmer. IrriMan: irrigation scheduling based on "Irriframe" model. PlaSoMan: irrigation scheduling based on the smart system that monitors both plant water content and soil moisture.

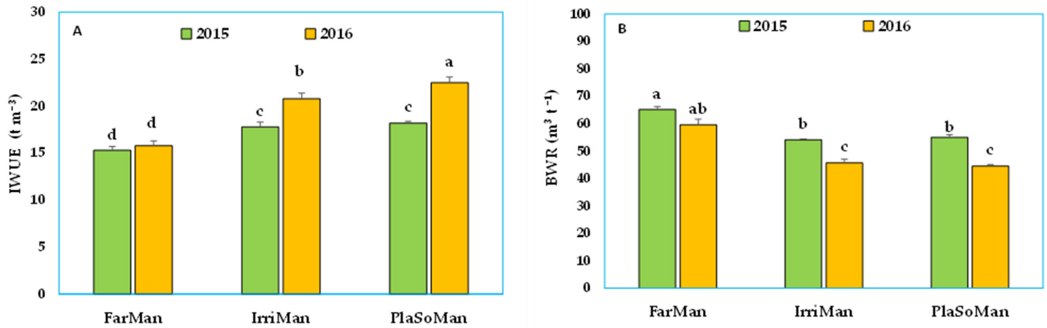

Figure 4. Effect of the interaction year × irrigation scheduling method on the irrigation water use efficiency for marketable yield (IWUE; (**A**)) and blue water requirement (BWR; (**B**)). Tukey HSD significant differences ($p < 0.05$) are indicated by different letters. Data are reported as means ± standard errors (n = 4). FarMan: irrigation scheduling managed by the farmer. IrriMan: irrigation scheduling based on "Irriframe" model. PlaSoMan: irrigation scheduling based on the smart system that monitors both plant water content and soil moisture.

Table 4. Effects of the irrigation scheduling mode on the main qualitative parameters.

Parameter	Irrigation Scheduling Method *		
	FarMan	**IrriMan**	**PlaSoMan**
Soluble solids content (°Brix)	4.0 ± 0.06 ^{c}	4.7 ± 0.09 ^{b}	5.0 ± 0.04 ^{a}
Color index (-)	1.1 ± 0.08 ^{b}	1.2 ±0.01 ^{ab}	1.3 ± 0.04 ^{a}
Titratable acidity (g citric acid 100 mL^{-1} fresh juice)	0.25 ± 0.02 ^{a}	0.24 ± 0.01 ^{a}	0.24 ± 0.01 ^{a}
pH	4.56 ± 0.1 ^{a}	4.39 ± 0.1 ^{a}	4.38 ± 0.1 ^{a}
Lycopene (mg 100 g^{-1} FW)	16.5 ± 2.1 ^{b}	17.6 ± 3.2 ^{a}	19.2 ± 2.1 ^{a}
Vitamin C (mg 100 g^{-1} FW)	22.5 ± 3.3 ^{b}	21.8 ± 2.2 ^{b}	25.5 ± 2.3 ^{a}
β-carotene (mg 100 g^{-1} FW)	0.88 ± 0.08 ^{b}	0.99 ± 0.03 ^{ab}	1.01 ± 0.05 ^{a}

* FarMan: irrigation scheduling managed by the farmer. IrriMan: irrigation scheduling based on "Irriframe" model. PlaSoMan: irrigation scheduling based on the smart system that monitors both plant water content and soil moisture. Tukey HSD significant differences ($p < 0.05$) are indicated by different letters. Data are reported as means ± standard errors (n = 8).

PCA Analysis

A principal component analysis (PCA) was performed on the correlation matrix relative to productive and efficiency parameters. The results of PCA allowed two factors to be identified, explaining 50% and 36.7% of the total variance, respectively (Table 5). The first factor (PC1) was highly and positively associated with marketable yield and blue water requirement, and highly and negatively associated with IWUE. Thus, PC1 could be considered a factor linked to a situation of high production with poor resource efficiency. The second factor (PC2) was positively associated with water productivity and yield quality. Therefore, PC2 could be considered a factor related to high-quality and water-friendly production (Table 5).

Table 5. Correlation coefficients between quantitative variables and the first two principal components (PC), with indication of the explained variance.

Selected Quantitative Variables	PC1	PC2
Marketable yield	0.67 **	−0.52 *
YQ	0.51 *	0.75 ***
WP_{YQ}	−0.12 ^{ns}	0.98 ***
IWUE	−0.93 ***	−0.12 ^{ns}
BWR	0.94 ***	−0.03 ^{ns}
Percentage explained variation	50.0%	36.7%
Total percentage explained variation	86.7%	

YQ: yield quality indicator; WP_{YQ}: water productivity for yield quality; IWUE: irrigation water use efficiency for marketable yield; BWR: blue water requirement. Significance codes: *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; ^{ns} = not significant.

Figure 5 reports the biplot relative to the principal component analysis. The red cross symbols indicate the centroid of the categorical variable “irrigation scheduling method”. Based on this, IrriMan and PlaSoMan were separated from FarMan along PC1, which is linked to situations of high productivity but poor water resource efficiency. FarMan was positioned on the positive side, while IrriMan and PlaSoMan were on the negative side. On the other hand, IrriMan and PlaSoMan were separated along PC2, which is associated with high-quality and water-friendly production. PlaSoMan was placed on the positive side, and IrriMan was on the negative. Finally, the two years (2015 and 2016) whose centroids were indicated with black cross symbols were separated along both factors, with 2015 positioned on the positive side, and 2016 on the negative one for both PCs.

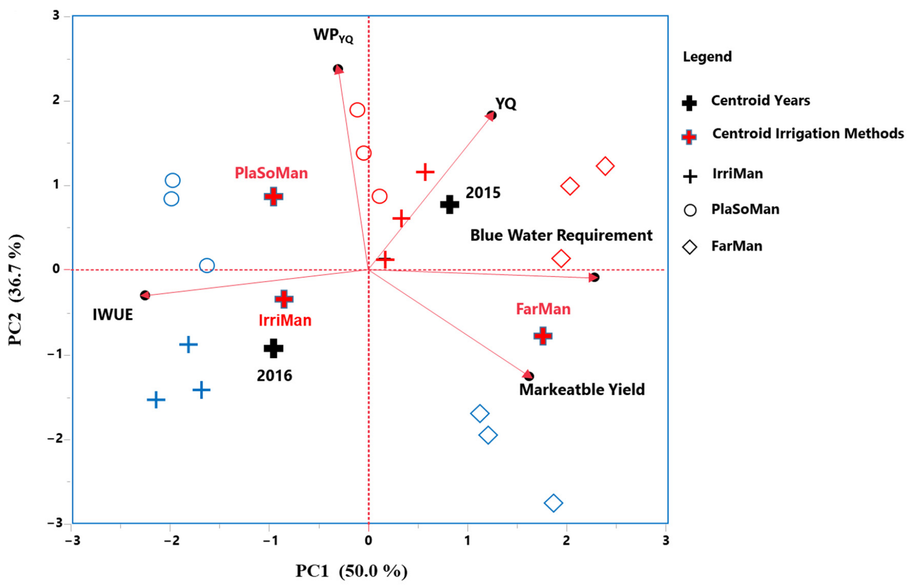

Figure 5. Biplot relative to the principal component analysis performed on marketable yield, yield quality indicator (YQ), water productivity for yield quality (WP_{YQ}), irrigation water use efficiency for marketable yield (IWUE) and blue water requirement. The red crosses indicate the centroids of the categorical variable, irrigation scheduling methods (FarMan: irrigation scheduling managed by the farmer; IrriMan: irrigation scheduling based on “Irriframe” model; PlaSoMan: irrigation scheduling based on the smart system that monitors both plant water content and soil moisture). The black crosses indicate the centroids of the experimental year (2005 and 2006). Red and blue symbols are relative to 2015 and 2016, respectively.

4. Discussion

As the demand for water continues to rise, it is essential to manage this finite resource through an integrated approach that considers the needs of agriculture, the environment, and society as a whole [7]. In various studies, deficit irrigation has been suggested as the primary method for water saving [23]. Our research aims to assess three different irrigation planning techniques to determine whether implementing more effective scheduling methods could lead to water saving while maintaining the quality and yield of processing tomato crops, without resorting to a deficit irrigation strategy. This study compared the irrigation techniques entirely overseen by the farmer (FarMan) to a model based on water balance (IrriMan), which calculates crop water needs using evapotranspiration data [11], as well as a smart irrigation scheduling system. This new system monitored both plant water status and soil moisture level by wireless sensors (PlaSoMan) and was the focus of the study's novelty.

As far as we know, most irrigation models and decision support systems (DSS) for irrigation scheduling rely on simulated plant evapotranspiration consumption [24]. However, it appears that none of these systems consider an evaluation of plant water status as the initial step for irrigation planning. Additionally, many irrigation modeling and DSS concentrate mainly on predicting water demand and suggesting various alternatives for irrigation management, putting the final decision-making responsibility on the farmer [25]. PlaSoMan system operates differently. It is fully automated and uses real-time data on the plant's water status and soil moisture levels to start or stop irrigation automatically. However, this requires a cost associated with purchasing and managing the system's various components over time. It was not surprising that FarMan had a higher yield compared to IrriMan and PlaSoMan, as it consumed the highest irrigation volume. In contrast, PlaSoMan was able to save approximately 30% of the water when compared to the irrigation scheduled by the farmer, and 7.5% compared to IrriMan. Despite this, PlaSoMan only experienced a yield loss of 10% and 2.5% compared to FarMan and IrriMan, respectively. These results indicate that PlaSoMan demonstrated a higher level of IWUE than the other two systems examined in this study, over the two-year period. This is a significant finding, since improving IWUE is crucial for maintaining food security, which is a significant challenge of this century [26].

Overall, the new smart system, which assesses both plant water status and soil moisture levels, appears to be an efficient solution for areas with limited water resources, where efficient water design and management are necessary for sustainability and agricultural competitiveness [27,28]. It is worth noting that IrriMan and PlaSoMan also had lower blue water requirement (BWR) values compared to FarMan. The blue water requirement refers to the irrigation freshwater consumed by the plant for a unit of product [8]. Therefore, sustainable irrigation systems are characterized by low blue water requirement values. The increase in the blue water requirement observed in the first year for all irrigation techniques was probably due to insufficient rainfall during crop growth, requiring more water for irrigation. This result confirms how water scarcity affects the use of blue water. Users need to become more efficient in using blue water as water becomes scarcer. However, this adaptation should be desirable in all regions, not just in those with low water availability and where blue water is the primary contributor to total crop water use [29]. To achieve high-quality tomato production through irrigation, a more comprehensive approach is needed beyond just focusing on yield. Both tomato yield and fruit quality parameters should be taken into consideration when managing irrigation. As such, it is crucial to explore the quantitative relationship between tomato yield, fruit quality, and water deficit to create an irrigation plan that promotes high-quality tomato production [30]. In our research, we utilized yield quality as a combined indicator of total yield and brix degree, the major determinant of processing tomato quality. PlaSoMan displayed the highest YQ value, indicating that the evaluation of both plant water status and soil moisture level effectively distributed water to achieve the optimal balance between quantity and quality, while also saving water resources. In addition to the above, PlaSoMan had the highest WP_{YQ} value compared to other irrigation scheduling methods. This value indicates how much total water, including precipitation and irrigation, was utilized to achieve YQ [4]. PlaSoMan's superior performance in achieving high-quality and water-friendly production placed it on the positive side of PC2 in the principal component analysis. Additionally, the YQ and WP_{YQ} responses remained stable over two years with the new smart irrigation scheduling method, which is particularly noteworthy considering ongoing climate change. Finally, to provide a comprehensive understanding, it is worth mentioning that the PlaSoMan system also yielded the greatest levels of lycopene, β-carotene, and vitamin C content in the fruit, which are nutrients beneficial for humans [30].

5. Conclusions

The decreasing availability of water for irrigation has become a growing worldwide concern, and advancements in technology are helping to address the challenge of improving irrigation water use efficiency. When it comes to producing high-quality tomatoes, both tomato yield and fruit quality parameters must be taken into consideration in irrigation management. In this study, the PlaSoMan smart system assessing both plant water status and soil moisture levels proved to be more effective, resulting in higher irrigation water use efficiency compared to the other two systems examined. Additionally, both the IrriMan and PlaSoMan systems had lower blue water requirement values than FarMan, appearing as a more sustainable irrigation system. By utilizing PlaSoMan, farmers can save water, obtaining both environmental and economic benefits while producing high-quality crops valued by the processing industry, leading to higher prices.

Author Contributions: Conceptualization, G.G. and M.M.G.; methodology, G.G., M.M.G. and F.C.; validation, G.G. and M.M.G.; formal analysis, F.C. and A.G.; investigation, G.G., M.M.G. and F.C.; writing—original draft preparation, F.C. and A.G.; writing—review and editing, M.M.G., G.G. and F.C.; visualization, F.C. and A.G.; supervision, G.G. and M.M.G.; project administration, G.G. and M.M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This study was part of the "Use of Innovative Systems Based on Wireless Sensor Networks in the Irrigation Scheduling of Processing Tomato" Project (SIWIP—DM 15531/7818/2013), funded by the Italian Ministry of Agricultural, Food and Forestry Policies (MiPAAF).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used and/or analyzed during the current study will be available from the authors upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. World Processing Tomato Council (WPTC). 2021. Available online: https://www.wptc.to/ (accessed on 22 May 2023).
2. Nemeskéri, E.; Neményi, A.; Bocs, A.; Pék, Z.; Helyes, L. Physiological Factors and their Relationship with the Productivity of Processing Tomato under Different Water Supplies. *Water* **2019**, *11*, 586. [CrossRef]
3. Laranjeira, T.; Costa, A.; Faria-Silva, C.; Ribeiro, D.; Ferreira de Oliveira, J.M.P.; Simões, S.; Ascenso, A. Sustainable Valorization of Tomato By-Products to Obtain Bioactive Compounds: Their Potential in Inflammation and Cancer Management. *Molecules* **2022**, *27*, 1701. [CrossRef] [PubMed]
4. Giuliani, M.M.; Gatta, G.; Cappelli, G.; Gagliardi, A.; Donatelli, M.; Fanchini, D.; De Nart, D.; Mongiano, G.; Bregaglio, S. Identifying the most promising agronomic adaptation strategies for the tomato growing systems in Southern Italy via simulation modeling. *Eur. J. Agron.* **2019**, *111*, 125937. [CrossRef]
5. Report FAO. *New Dimensions in Water Security—Water, Society and Ecosystem Services in the 21st Century*; Food and Agriculture Organization of the United Nations Land and Water Development Division: Rome, Italy, 2000.
6. Hellín, H.N.; Martínez-del-Rincon, J.M.; Domingo-Miguel, R.; Soto-Valles, F.; Torres-Sánchez, R. A decision support system for managing irrigation in agriculture. *Comput. Electron. Agric.* **2016**, *124*, 121–131. [CrossRef]
7. Chand, J.; Hewa, G.; Hassanli, A.; Myers, B. Evaluation of Deficit Irrigation and Water Quality on Production and Water Productivity of Tomato in Greenhouse. *Agriculture* **2020**, *10*, 297. [CrossRef]
8. Ventrella, D.; Giglio, L.; Garofalo, P.; Dalla Marta, A. Regional assessment of green and blue water consumption for tomato cultivated in Southern Italy. *J. Agric. Sci.* **2017**, *156*, 689–701. [CrossRef]

9. Rinaldi, M.; Garofalo, P.; Rubino, P.; Steduto, P. Processing tomatoes under different irrigation regimes in Southern Italy: Agronomic and economic assessments in a simulation case study. *Ital. J. Agrometeorol.* **2011**, *3*, 39–56.
10. Giuliani, M.M.; Gatta, G.; Nardella, E.; Tarantino, E. Water saving strategies assessment on processing tomato cultivated in Mediterranean region. *Ital. J. Agron.* **2016**, *11*, 738. [CrossRef]
11. Giannerini, G.; Genovesi, R. The water saving with Irriframe platform for thousands of Italian farms. *J. Agric. Inform.* **2013**, *6*, 49–55. [CrossRef]
12. Doorenbos, J.; Pruit, W.O. *Crop Water Requirements*; FAO Irrigation and Drainage Paper 24; FAO: Rome, Italy, 1977; p. 144.
13. Driessen, P.M. The water balance of the soil. In *Modelling of Agricultural Production: Weather, Soils and Crops*; van Keulen, H., Wolfm, J., Eds.; Pudoc: Ilocos Sur, Philippines, 1986; pp. 76–116. Available online: https://edepot.wur.nl/172091 (accessed on 6 March 2023).
14. Available online: https://www.irriframe.it/Irriframe (accessed on 6 March 2023).
15. Idso, S.B.; Reginato, R.J.; Jackson, R.D.; Pinter, P.J., Jr. Measuring yield-reducing plant water potential depressions in wheat by infrared thermometry. *Irrig. Sci.* **1981**, *2*, 205–212. [CrossRef]
16. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper 56; FAO: Rome, Italy, 1998; Available online: https://www.fao.org/3/x0490e/x0490e00.htm (accessed on 16 June 2023).
17. Giuliani, M.M.; Nardella, E.; Gagliardi, A.; Gatta, G. Deficit irrigation and partial root-zone drying techniques in processing tomato cultivated under Mediterranean conditions. *Sustainability* **2017**, *9*, 2197. [CrossRef]
18. Official Methods of Analysis (AOAC), 16th ed.Association of Official Analytical Chemists: Washington, DC, USA, 1995.
19. Francis, F.J.; Clydesdale, F.M. *Food Colorimetry: Theory and Applications*; AVI Publishing Co.: Westport, CT, USA, 1975. [CrossRef]
20. Favati, F.; Lovelli, S.; Galgano, F.; Miccolis, V.; Di Tommaso, T.; Candido, V. Processing tomato quality as affected by irrigation scheduling. *Sci. Hortic.* **2009**, *122*, 562–571. [CrossRef]
21. Ishiwu, C.N.; Iwouno, J.O.; Obiegbuna, J.E.; Ezike, T.C. Effect of thermal processing on lycopene, beta-carotene and Vitamin C content of tomato [Var.UC82B]. *J. Food Nutr. Sci.* **2014**, *2*, 87–92. [CrossRef]
22. Box, G.; Cox, D. An analysis of transformations. *J. R. Stat. Soc. Ser. B Methodol.* **1964**, *26*, 211–252. [CrossRef]
23. Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in Gagliardi dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [CrossRef]
24. Buono, V.; Gatta, G.; Riezzo, E.; Manes, A.; Nardella, E.; Gagliardi, A.; Carucci, F.; Giuliani, M.M. Experimental testing of a model-based decision support system integrated with smart sensors to optimize irrigation strategies for processing tomato: A case study in southern Italy. *Acta Hortic.* **2021**, *1311*, 485–492. [CrossRef]
25. Bonfante, A.; Monaco, E.; Manna, P.; De Mascellis, R.; Basile, A.; Buonanno, M.; Cantilena, G.; Esposito, A.; Tedeschi, A.; De Michele, C.; et al. LCIS DSS—An irrigation supporting system for water use efficiency improvement in precision agriculture: A maize case study. *Agric. Syst.* **2019**, *176*, 102646. [CrossRef]
26. Hassanli, A.M.; Ahmadirad, S.; Beecham, S. Evaluation of the influence of irrigation methods and water quality on sugar beet yield and water use efficiency. *Agric. Water Manag.* **2010**, *97*, 357–362. [CrossRef]
27. Le, T.A.; Pék, Z.; Takács, S.; Neményi, A.; Daood, H.G.; Helyes, L. The effect of plant growth promoting rhizobacteria on the water-yield relationship and carotenoid production of processing tomatoes. *HortScience* **2018**, *53*, 816–822. [CrossRef]
28. Martínez, J.; Reca, J. Water use efficiency of surface drip irrigation versus an alternative subsurface drip irrigation method. *J. Irrig. Drain. Eng.* **2014**, *140*, 04014030. [CrossRef]
29. Chouchane, H.; Hoekstra, A.Y.; Krol, M.S.; Mekonnen, M.M. The water foot print of Tunisia from an economic perspective. *Ecol. Indic.* **2015**, *52*, 311–319. [CrossRef]
30. Chen, J.; Kang, S.; Du, T.; Qiu, R.; Guo, P.; Chen, R. Quantitative response of greenhouse tomato yield and quality to water deficit at different growth stages. *Agric. Water Manag.* **2013**, *129*, 152–162. [CrossRef]