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Potential Use of Superabsorbent Polymer on Drought-Stressed Processing Tomato (*Solanum lycopersicum* L.) in a Mediterranean Climate

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Abstract: Drought risk is significantly increasing as a consequence of climate change, and the Mediterranean basin will be among the most affected areas by water scarcity in Europe. The development of agronomic strategies enabling the reduction in drought stress in cultivated crops is, therefore, a crucial priority. Superabsorbent polymers (SAPs) are soil amendments capable to retain water and release it when drought occurs. In the present study, the ability of a commercial SAP to improve the drought tolerance of processing tomato (*Solanum lycopersicum* L.) was assessed on a commercial farm located in northern Italy. A strip plot experimental design was adopted, where three irrigation treatments (IRR_{100}, IRR_{75}, and IRR_{50}, respectively, restituting 100%, 75%, and 50% of crop evapotranspiration) were combined with the application of the SAP (control vs. soil amended with SAP). No significant interaction was observed between irrigation treatments and SAP application in yield and quality traits. SAP application allowed for an average increase in tomato yield (+16.4%) and irrigation water use efficiency (IWUE) (+15.8%), determined by a higher number of marketable fruits. The irrigation strategy IRR_{75} + SAP maintained the same yield and quality as the full irrigation control (IRR_{100}), increasing the IWUE by about 37%. The experiment demonstrated that, for processing tomatoes grown in the Mediterranean, it is possible to reduce the water supply by 25% when SAP amendment is applied to the soil.

Keywords: superabsorbent polymer; processing tomato; deficit irrigation; drought tolerance; water-saving strategies

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1. Introduction

Water scarcity is a major challenge to crop productivity under changing climate conditions, especially in arid and semi-arid regions [1]. In the Mediterranean area, irrigation is of vital importance for food security and economic development, despite the water shortage characterizing this area [2]. While climate change will affect water timing and distribution, the rising global population will determine an increase in water demand (especially by cities) in the upcoming decades, with potential conflicts for the agricultural water allocation [3]. Currently, agriculture uses 70% of the accessible freshwater globally, but almost 35% of this is wasted due to leaky irrigation systems and inefficient irrigation water management [4,5]. Additionally, irrigation requirements by agriculture are expected to increase in the near future, not only because of climate change but also as a consequence of the increasing food demand [2,4]. Therefore, improving water use efficiency in the agricultural sector is urgent [3]. Nonetheless, agriculture is also the sector with the largest scope for improvement [6]. Fader et al. [2] estimated the implementation of more efficient irrigation systems can enable the reduction of up to 35% of irrigation water requirements. Accordingly, developing new water-saving irrigation strategies is a crucial priority. Currently, different strategies are widely studied for optimizing water use efficiency (WUE), and deficit irrigation is among the most studied [7,8]. Furthermore, soil application of superabsorbent polymers (SAPs) is a new water-saving strategy that is gaining attention [9–11]. Superabsorbent polymers are macromolecular cross-linked hydrophilic polymer chains with the ability to absorb water or aqueous fluids through an osmotic process [12,13]. When the polymer is applied to the soil, water from irrigation and rainfall is absorbed by the polymer, acting as an additional water reservoir. Then, as the soil dries, the absorbed water is released, making it available to the plants [13]. These materials are generally safe and non-toxic since the polymer chains are biodegraded by soil microbes through mineralization into carbon dioxide, water, ammonia, and potassium ions [14,15]. SAPs are considered soil improvers, as they can positively influence some physical and chemical characteristics. Accordingly, previous studies in the literature show that the swelling of the polymer in the soil positively affects soil porosity, increasing air capacity [16], but it is also known to increase the cation exchange capacity and decrease the soil infiltration rate [17]. However, one of the main purposes of their use in agriculture is to improve the soil water status, allowing crops to overcome drought periods, thus limiting the damage caused by water stress. The application of SAPs to soil is known to increase water availability in the root zone for absorption by plants, by increasing the soil's water-holding capacity [9,18]. Positive effects on plant growth indicators were reported as a consequence of the application of SAPs to the soil in rosemary, such as the seedling establishment percentage, fresh biomass production, and plant height [17]. Several studies proved that the application of SAPs to the soil enhanced water use efficiency in different crops, such as beans [11,19], maize [10], and peanuts [20]. Therefore, SAPs have the potential to be included in water deficit irrigation strategies. Accordingly, Satriani et al. [11] demonstrated that is possible to reduce up to 30% of irrigation water when a SAP is applied to the soil in a Mediterranean environment, but more water-saving irrigation strategies have to be developed for other water-demanding crops, such as processing tomato.

Processing tomato (*Solanum lycopersicum* L.) is among the vegetable crops mostly cultivated in the Mediterranean basin, especially in Italy [21]. The tomato crop is highly sensitive to water stress; indeed, drought is known to have injurious effects on growth, development, and yield [22,23]. Since water supply is undoubtedly among the main problems for processing tomato cultivation, new water-saving strategies are needed to be investigated. The present study aims to assess the effects of a commercial SAP on the yield and quality of processing tomatoes in a Mediterranean climate under different degrees of drought stress. Additionally, new water-deficit irrigation strategies that integrate the adoption of the SAP are compared. The assumption is that plants treated with SAP can increase drought tolerance and improve the irrigation water use efficiency (IWUE).

2. Materials and Methods

2.1. Location and Experimental Design

The experiment was carried out during the summer season (between June and September 2021) on a commercial farm located in Rivarolo Mantovano (MN), in northern Italy (45°04′41″ N and 10°28′04″ E, 26 m a.s.l.). The local climate is Cfa type according to the Koppen classification. Soil texture is classified as sandy according to the USDA classification and is a Cambisol (IUSS, 2014). The characteristic of soil used for experimentation was as follows: sand = 53.7%, silt = 46.3%, clay = 0%; pH = 8.12; total $CaCO_3$ = 99.1 g kg^{-1}; bulk density = 1.34 g cm^{-3}; total organic matter (TOM) = 1.95%; total nitrogen = 1.41 g kg^{-1}; the wilting point (WP) and field capacity (FC) were 6.48% v:v and 21.9% v:v, respectively.

To assess the interactions between drought stress levels and the application of a superabsorbent polymer (SAP) to the soil, a two-factor strip-plot experiment with three replicates was set up. Three irrigation treatments in the main plots were randomized, while in the subplot, two levels of the superabsorbent polymer were applied to the soil (non-treated control vs. SAP-treated). During the whole crop cycle, starting 14 days after the transplant, the irrigation treatments restored 100%, 75%, and 50% of crop evapotranspiration ET_c, henceforth called IRR_{100}, IRR_{75}, and IRR_{50}, respectively.

2.2. Materials and Growing Conditions

All the agronomical operations followed the common farmers' practices of the region. Processing tomato (*Solanum lycopersicum* L. cv. Heinz 3604) was transplanted in a double-row cropping system at 36,765 plants ha^{-1} (0.5 m distance between the single rows, 1.6 m between the center of the double row, and 0.34 m within the row). A drip irrigation system was used, which consisted of 22 mm PE laterals with drippers spaced at 0.3 m. A single drip line per two plant rows was used, with 1 l h^{-1} discharge measured at 1 bar operating pressure. At planting, nitrogen, phosphorus, and potassium were applied at the rates of 150, 100, and 180 kg ha^{-1}, respectively. The tested SAP was a potassium polyacrylate-based molecule (Evonik Industries, Essen, Germany) commercialized in Italy with the label RainPower (Endofruit, Bussolengo, Italy). The SAP was localized in the furrow at 8 cm below the transplanting lines through a micro-granulator (25 kg ha^{-1}).

2.3. Crop Evapotranspiration (ET_c) and Irrigation Management

The irrigation management was based on the estimation of crop evapotranspiration (ET_c), restoring 100%, 75%, and 50% of ET_c according to the respective irrigation treatment. ET_c was calculated using the double K_c factor, according to the FAO guidelines, paper 56 [24] using the following equation:

$$ET_c = ET_0 \times (K_{cb} + K_e) \tag{1}$$

where ET_c (mm day^{-1}) is the crop evapotranspiration, ET_0 is the reference evapotranspiration (mm day^{-1}), and the sum (K_{cb} + K_e) represents the double crop coefficient calculated according to the FAO guidelines [24].

The estimation of ET_0 was performed using the Penman–Monteith formula, which is shown in Equation (2):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation water pressure (kPa), e_a is the actual water pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}).

All climatic data were measured by a weather station localized in the field.

The irrigation water was applied whenever the readily available water (RAW) was completely depleted. RAW was determined as follows:

$$RAW = (FC - WP)\ p\ Z_n \tag{3}$$

where FC and WP are, respectively, the field capacity and the wilting point (mm m^{-1}), p is the depletion factor (0.4 for tomato), and Z_n is the root depth (m) during the crop cycle (from 0.2 m at the initial growth stage up to 0.7 m). Soil water moisture was daily estimated and monitored by computing the soil water balance hereby reported (Equation (4)).

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i - ET_{c,i} + DP_i \tag{4}$$

where $D_{r,i}$ is the water depletion in the root zone at the end of day i (mm), $D_{r,i-1}$ water depletion in the root zone at the end of the previous day (mm), P_i is the precipitation on day i (mm), RO_i is the runoff from the soil surface on day i (mm), I_i is the net irrigation in day i that infiltrates the soil (mm), CR_i is the capillary rise from the groundwater on day i, $ET_{c,i}$ is the crop evapotranspiration estimated for day i (mm), and DP_i is the water loss out of the root zone by deep percolation on day i (mm) [24].

2.4. Plant Measurements

At harvest, which occurred at the 87–88 stage according to the BBCH phenological scale [25], three plants per subplot were randomly sampled in the field to determine yield. Total fruits were classified and separately counted as marketable (ripe) and unmarketable (unripe, overripe, and damaged). Accordingly, the total and marketable yield (ton ha^{-1}) and fruit number, average fruit weight (g), and fresh vegetative biomass (stem and leaf) (g $plant^{-1}$) were determined. Irrigation water use efficiency (IWUE, g L^{-1}) was calculated as the ratio between the fresh weight of the commercial biomass (g m^{-2}) and the water applied with irrigation (L m^{-2}) [26].

Then, four fruits per plant were randomly chosen to determine the qualitative measurement. Before the measurements, the fruits were stored in the refrigerator at 4 °C degrees for 2 days. One fruit per plant was chosen for the determination of fruit dry weight, after oven-drying at 65 °C until a constant weight was reached. On the remaining three fruits, the following measures were taken: Maximum fruit diameter (mm) was determined with an electronic caliper. Fruit color was assessed with a CR 200 Chroma-Meter Colorimeter (Konica Minolta, Sensing, Tokyo, Japan), taking three measures on the equatorial plane of each fruit, and $(a^*/b^*)^2$ was calculated given the existing correlation with lycopene concentration [27]. Fruit firmness was determined with an electronic penetrometer (8 mm diameter probe) after removing the peel on one side with a manual mandolin. Then, the three fruits were smoothed together to obtain juice. The total soluble solids (TSSs, expressed as °Brix) were determined with a digital refractometer (PAL-1 Atago, Tokyo, Japan), while the pH and total acidity of the fruit were determined with a Titromatic instrument (Crison, Barcelona, Spain) after mixing 10 mL of tomato juice with 30 mL of distilled water.

2.5. Statistical Analysis

Data were analyzed using two-way ANOVA, and means were separated with the Tukey HSD test at $p < 0.05$. Before the analysis, the normality and heteroscedasticity were checked with the Shapiro–Wilk test and Levene test, respectively. Means and standard errors (SEs) were also calculated. R software (version 3.3.2, packages "car" and "emmeans") was used (R Development Core Team, Vienna, Austria).

3. Results

3.1. Climate during the Experiment

During the experiment, the maximum daily air temperature ranged between 26.6 °C and 39.2 °C, with an average of 33.1 °C. The minimum daily temperature ranged between 12.2 °C and 21.0 °C (average 17.3 °C). Concerning the relative humidity, the maximum daily value varied between 74% and 98% (91.4% on average), while the minimum varied between 27% and 72% (38.7% on average). The daily average ET_c was 4.53 mm d^{-1}. The cumulative ET_c during the experiment was 482 mm, which was almost completely restored in IRR_{100} through irrigation (351 mm) and effective rainfalls (57.2 mm) during the crop cycle. The restoration of ET_c in IRR_{100} was not complete, given the necessity to stop the irrigations before the harvest to increase the soluble solids content of the fruits, as commonly performed by the farmers. Accordingly, the irrigation volumes in IRR_{75} and IRR_{50} were 263 mm and 175 mm, respectively.

3.2. Morphological and Productive Parameters

No significant interaction was detected between irrigation treatment and SAP application for any parameters assessed, as reported in Table 1. Marketable yield, total and marketable fruits, and IWUE were significantly affected by irrigation treatment and also by the application of SAP to the soil (Table 1).

Table 1. Results of two-way ANOVA analysis on yield component and morphological parameters of processing tomato grown under different irrigation treatments (IRR) factorially combined with the application of two levels of a superabsorbent polymer (SAP-treated and non-treated control). Interaction results are also described (IRR × SAP).

Treatments	Marketable Yield	Total Fruits	Marketable Fruits	Fruit Weight	Dry Matter	Fresh Biomass	HI	IWUE
Irrigation (IRR)	***	***	***	ns	ns	**	ns	***
F-value	16.27	25.17	17.05	1.22	1.77	13.50	0.782	58.66
p-value	<0.001	<0.001	<0.001	0.334	0.219	1.14×10^{-3}	0.483	<0.001
Sum of square	1406	367	209	5.85	0.463	158,335	0.001	768
SAP application (SAP)	**	***	***	ns	ns	ns	ns	**
F-value	18.50	24.49	22.65	0.014	1.22	0.725	3.12	20.79
p-value	1.15×10^{-3}	<0.001	<0.001	0.909	0.295	0.414	0.107	1.04×10^{-3}
Sum of square	799	178	139	0.033	0.159	4252	0.003	136
IRR × SAP	ns	ns	ns	ns	ns	ns	ns	ns
F-value	0.118	0.458	0.389	3.97	0.288	1.46	0.595	0.912
p-value	0.890	0.645	0.687	0.054	0.755	0.278	0.570	0.432
Sum of square	10.27	6.68	4.78	18.96	0.075	17,120	0.001	11.96

HI stands for “harvest index”, IWUE for “irrigation water use efficiency”. ** $p < 0.01$, *** $p < 0.001$, ns “not significant”.

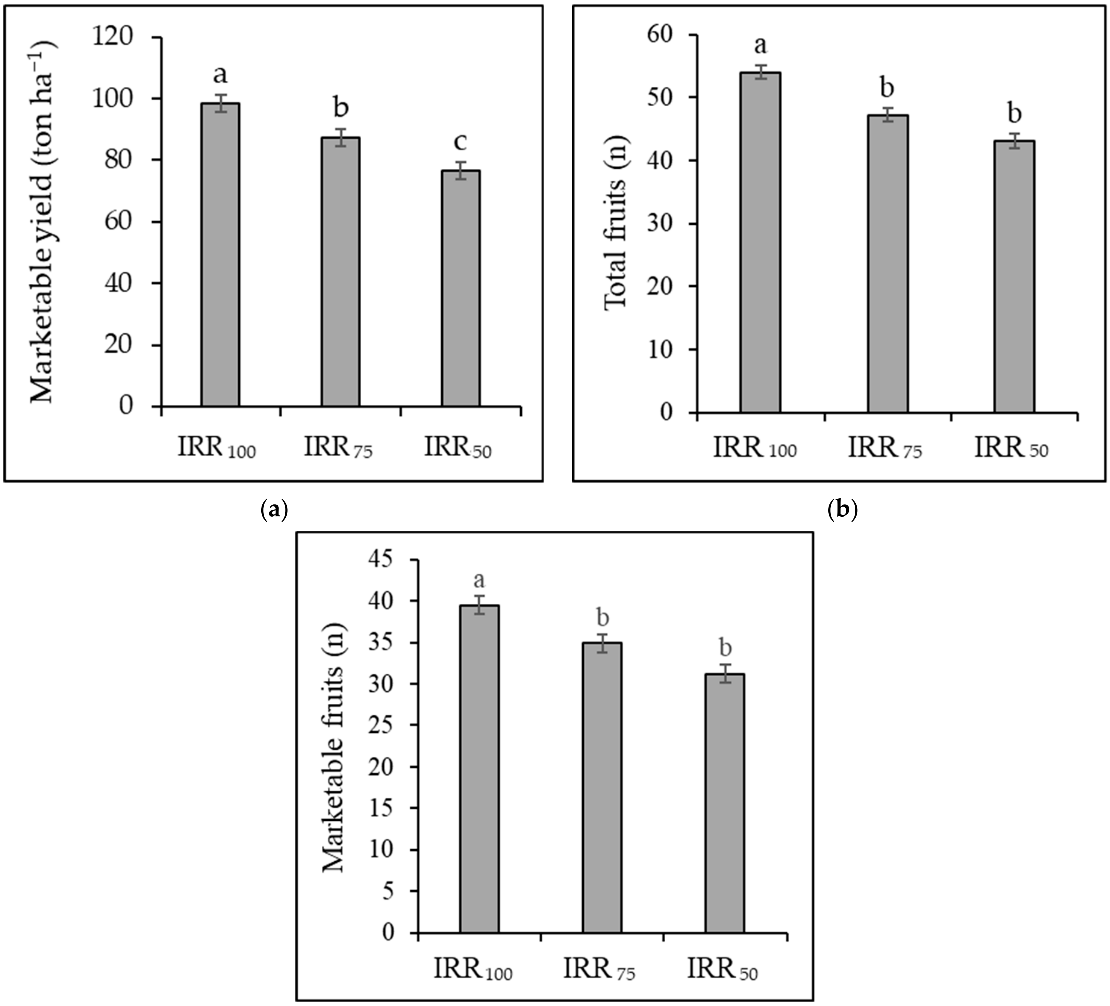
The marketable yield trend reflected the irrigation treatments, with the highest yield detected in IRR_{100}, followed by IRR_{75} and IRR_{50} (Figure 1a). Plants grown under full irrigation (IRR_{100}) produced the greatest number of total and marketable fruits (54 and 39, respectively) (Figure 1b,c). The IRR_{75}- and IRR_{50}-treated plants produced statistically comparable numbers of total and marketable fruits (45 and 33 as mean values, respectively), which resulted in a reduction of 16.3%, compared with IRR_{100} (Figure 1b,c).

Moreover, the irrigation treatments significantly affected the fresh vegetative biomass (Table 1). No significant difference was observed in fresh biomass produced by plants grown under IRR_{75} and IRR_{50} treatments (801 g plant^{-1} and 709 g plant^{-1}, respectively). Contrariwise, the fresh vegetative biomass produced using IRR_{100} (937 g plant^{-1}) was significantly higher (+19.4%) than the values observed in water-stressed treatments (data not shown). Fruit weight, fruit dry matter, and harvest index (HI) were not affected by irrigation treatments (Table 1).

SAP application did not significantly affect fruit weight, fruit dry matter, fresh vegetative biomass production, and HI (Table 1). Nonetheless, SAP application led to an increase in marketable yield (+16.4%) (Figure 2a), total fruit number (+14%), and marketable fruit number (+17.2%) (Figure 2b,c), compared with non-treated control.

The IWUE was significantly affected by irrigation treatments and by the application of SAP as well (Figure 3). Accordingly, the IWUE progressively increased as the amount of water applied through irrigation was reduced as a consequence of irrigation treatment (Figure 3a). In particular, the IRR_{50} and IRR_{75} treatments determined an increase in the IWUE of about 56% and 18.5%, respectively, compared with IRR_{100} (Figure 3a). Moreover, the IWUE was significantly increased by SAP application (+15.8%), as shown in Figure 3b.

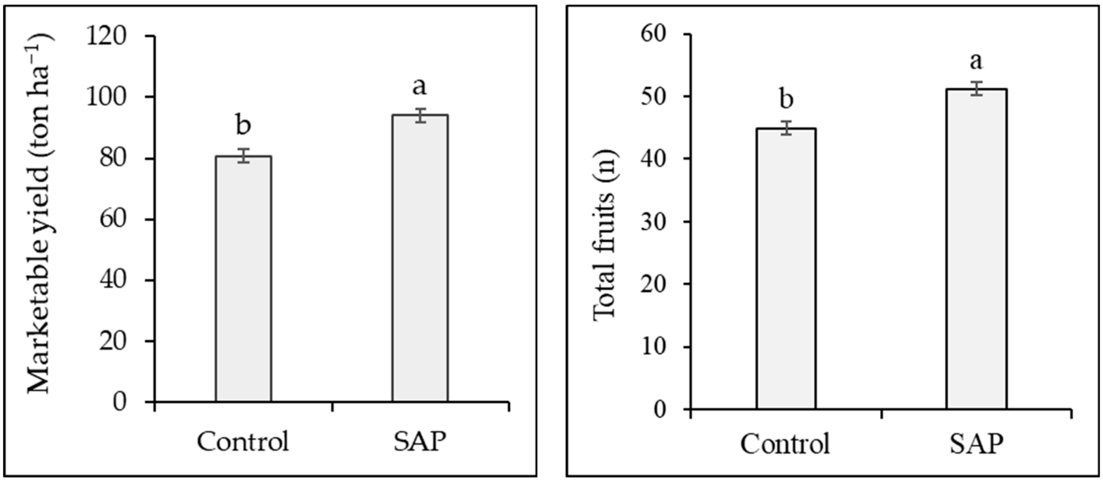
The combined effect of both strategies (irrigation treatments and SAP application) is reported in Figure 4, which resulted in a significant increase in the IWUE. IRR_{50} + SAP determined a significant increase of +79% of the IWUE, compared with IRR_{100}. A slighter increase in the IWUE was determined by using the IRR_{75} + SAP strategy (+37%), compared with IRR_{100}. No significant differences were observed for the IRR_{100} + SAP strategy in comparison to IRR_{100} and IRR_{75} + SAP strategies.



(**a**) (**b**)

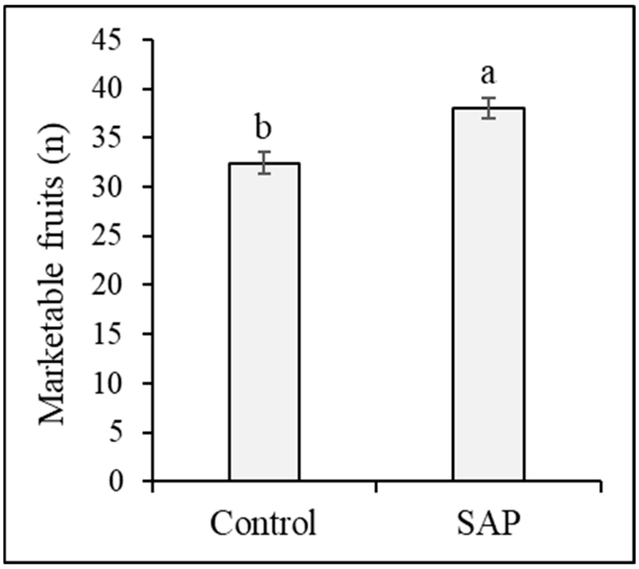
(**c**)

Figure 1. Effect of restoration of 100%, 75%, and 50% of ET_c as a consequence of irrigation treatments (IRR_{100}, IRR_{75}, and IRR_{50}, respectively) on (**a**) marketable yield and (**b**) total and (**c**) marketable fruits produced by plants. Different letters indicate significant differences at $p < 0.05$. Vertical bars represent standard errors.



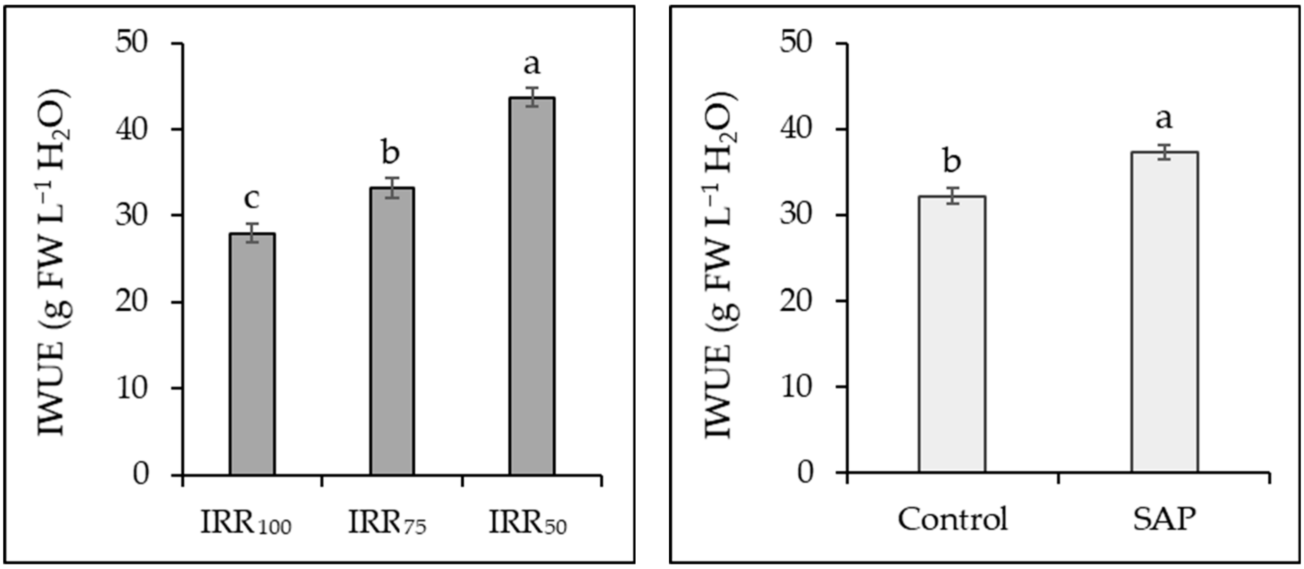
(**a**) (**b**)

Figure 2. *Cont.*



(**c**)

Figure 2. Effect of superabsorbent polymer (SAP) on (**a**) marketable yield and (**b**) total and (**c**) marketable fruits produced per plant. Different letters indicate significant differences at $p < 0.05$. Vertical bars represent standard errors.



(**a**) (**b**)

Figure 3. Single effect on irrigation water use efficiency (IWUE) determined by (**a**) irrigation treatments (100%, 75%, and 50% of ETc restoration, respectively IRR_{100}, IRR_{75}, and IRR_{50}) and (**b**) superabsorbent polymer applied to the soil (SAP-treated and non-treated control). Different letters indicate differences at $p < 0.05$. Vertical bars represent standard errors.

If the effective rainfalls were considered in the calculation of the WUE, the increase determined by IRR_{75} + SAP in comparison to the control strategy (IRR_{100}) was reduced to +30%, while for IRR_{50} + SAP, it was reduced to +57% (data not shown).

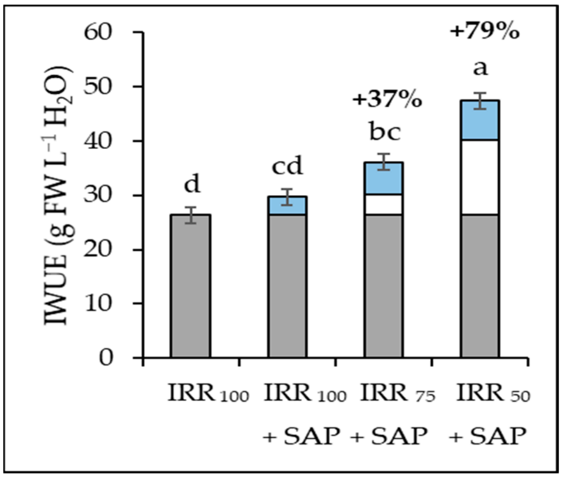


Figure 4. Effect on IWUE determined by the combination of irrigation treatment and SAP application to the soil. The white component of the columns represents the increase in the IWUE determined by the irrigation strategy (IWUE IRR), while the blue component is the increase in the IWUE determined by the application of SAP to the soil (IWUE SAP). Different letters indicate significant differences at $p < 0.05$. Vertical bars represent the standard error.

3.3. *Qualitative Parameters*

No significant interaction effect between irrigation treatment and the application of SAP for any qualitative parameters was detected (Table 2). Moreover, neither irrigation treatments nor SAP application significantly affected the qualitative parameters measured. The only exception was the sunburned fruits (expressed as % of the total fruit produced by a plant), which were significantly increased as the irrigation volumes decreased (Figure 5), reaching the maximum incidence of 9.3% in IRR$_{50}$, compared with IRR$_{100}$ (1.9%) and IRR$_{75}$ (2.5%). No significant difference was observed in sunburned fruits between IRR$_{100}$ and IRR$_{75}$. Furthermore, a significant negative correlation ($p < 0.05$) between the fresh vegetative biomass and the sunburned fruit rate was observed (Figure 6).

Table 2. Results of two-way ANOVA analysis on qualitative parameters of processing tomato grown under different irrigation treatments (IRR) factorially combined with the application of two levels of a superabsorbent polymer (SAP-treated and non-treated control). Results of interaction are also reported (IRR × SAP).

Treatments	Brix	pH	Titratable Acidity	Firmness	Color	Sunburn
Irrigation (IRR)	ns	ns	ns	ns	ns	***
F-value	0.084	0.250	0.500	0.384	3.152	33.73
p-value	0.920	0.783	0.620	0.690	0.086	<0.001
Sum of square	0.013	0.001	0.034	0.011	0.064	201
SAP application	ns	ns	ns	ns	ns	ns
F-value	0.472	0.248	0.189	0.119	1.556	0.001
p-value	0.507	0.629	0.673	0.736	0.240	0.972
Sum of square	0.038	7×10^{-4}	0.006	0.001	0.015	0.04
IRR × SAP	ns	ns	ns	ns	ns	ns
F-value	0.168	2.03	1.53	0.991	1.84	1.02
p-value	0.847	0.181	0.263	0.404	0.207	0.395
Sum of square	0.027	0.012	0.104	0.028	0.037	6.10^4

*** $p < 0.001$, ns "not significant".

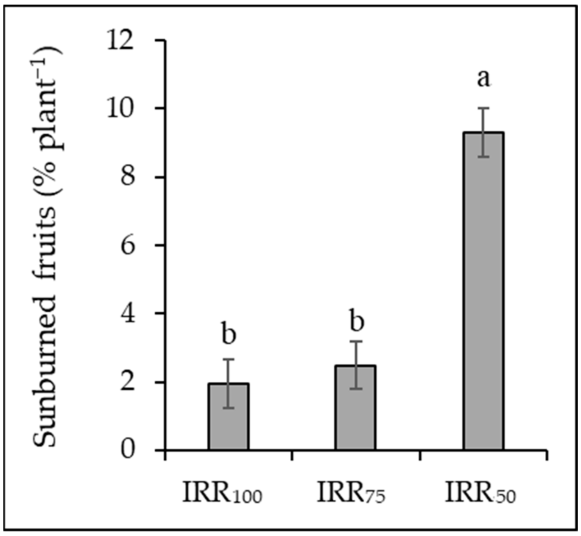


Figure 5. Effect of irrigation treatments on the percentage of sunburned fruits. Different letters indicate significant differences at $p < 0.001$. Vertical bars represent the standard errors.

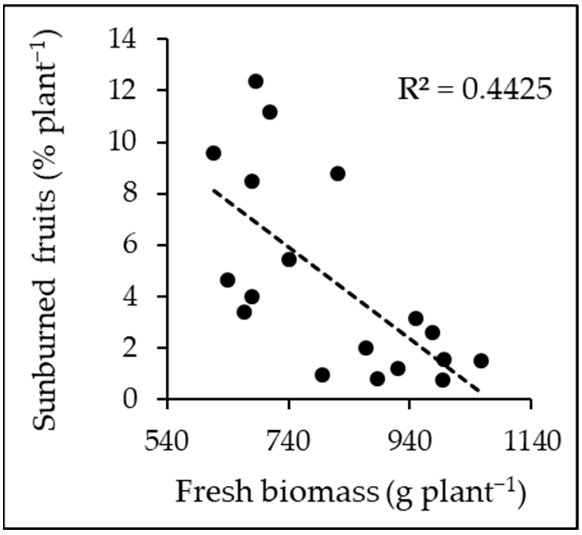


Figure 6. Relationship between biomass and sunburned fruits ($p < 0.01$) (n = 18).

4. Discussion

It is well known that water is a limiting factor in processing tomato production, as reported by previous studies in the literature [28–30], and water availability for irrigation will become a challenging issue in the Mediterranean basin because of climate change [2,4]. The progressive drought stress determined by treatments applied in the present study induced a significant reduction in the marketable yield of processing tomatoes (Figure 1a) [23,31]. Since fruit weight was not affected by irrigation treatments (Table 1), such a decrease in marketable yield can be associated with the reduction in marketable fruits number produced per plant, as observed in Figure 1c [32]. This result is in agreement with the findings of Zegbe-Dominguez et al. [33], who observed a significantly lower number of fruits for processing tomatoes cultivated under irrigation deficit conditions, compared with the fully irrigated control. Flowering is a phenological stage that can negatively be affected by abiotic stresses in several crops, and tomato is known to be vulnerable to drought stress during this growth stage [34]. The limited water availability determines a low stomatal conductance, reducing the CO_2 assimilation and, thus, the photosynthetic rate [35]. This physiological mechanism can lead to a decreased availability of photoassimilates used for the development of floral organs and posing to the abscission of flowers and flower buds [36,37], causing a reduced number of fruits per plant.

Although the reduction in water applied to the crop as a consequence of the irrigation treatment allowed for an increase in the IWUE (Figure 3a), the implementation of deficit irrigation strategies during the whole crop cycle is not recommended without a water stress tolerance strategy being in place, due to the negative effect on the marketable yield (Figure 1a). Accordingly, IRR_{75} suffered a reduction of 11.3% in the marketable yield in comparison to IRR_{100} (Figure 1a). Nonetheless, such a yield reduction in IRR_{75} was highly compensated by the application of SAP to the soil in the IRR_{75} + SAP strategy, allowing an increase in marketable yield (+16.4%) (Figure 2a) [38]. This was mainly due to the increase in the number of marketable fruits by the plants grown under SAP-treated soil (+17.2%), compared with the non-treated control (Figure 2c). As reported in the previous literature [39], the use of SAP in tomato cultivation can increase the number of flowers and fruits, compared with a non-treated control. Similar results have been previously reported [12], according to which an increase in yield of 16% in tomato cultivation grown in sandy soils treated with SAP in Spain and Italy was observed. Other previous studies [16,18] demonstrated that the addition of SAP to the growing media can improve its water-holding capacity and may be useful in providing water to plants during drought stress, especially if tomato plants are grown in sandy soils, as in the present study. Additionally, the imbibition of SAP leads to an increase in the soil's volume and porosity, resulting in better oxygenation of the root zone [40]. SAP application revealed also an increase in the IWUE of processing tomatoes (+15.8% on average) (Figure 3b) [41]. The irrigation strategy IRR_{75} + SAP allowed the combination of IWUE enhancement effect determined by adopting both strategies (deficit irrigation and SAP application to the soil), increasing it up to 37% compared with the control (IRR_{100}) (Figure 4).

The adoption of the IRR_{100} + SAP strategy did not lead to a significant increase in the IWUE (Figure 4) and yield (data not shown), compared with IRR_{100}; therefore, its adoption is not justified.

Throughout the experiment, IRR_{50} + SAP was the strategy that allowed for the highest IWUE (Figure 4). Nonetheless, it should be pointed out that the percentage of sunburn-damaged fruits was significantly higher in IRR_{50} (Figure 5) [42]. Higher percentages of sunburned fruits may entail significant reductions in the selling price, thus reducing the farmer's income [43]. The sunburned rate in IRR_{50} may be reflected in the lower fresh biomass produced by the severely stressed plants, which was not sufficient to protect the fruits from the intense solar radiation (Figure 6) [44]. It is widely known that sunburn in tomato fruits is related to an increase in solar radiation, which is responsible for chlorophyll degradation, but it can also be due to the exposure of mature-green tomatoes to temperatures above 30 °C, which inhibits lycopene biosynthesis, resulting in the typical yellow color of the fruit [45]. However, the application of SAP to the soil did not enhance the fresh green biomass production at harvest (Table 1); therefore, it resulted in not being useful in reducing the number of sunburned fruits. Montesano et al. [46] reported that the application of SAP in the growing media allowed for an increase in the fresh biomass of cucumber and basil. Nonetheless, the same authors also reported that the effect of SAP on the basil fresh biomass progressively decreased along the crop cycle, resulting in non-significant differences compared with the non-treated plants at harvest time. Accordingly, although IRR_{50} allowed for the highest irrigation water use efficiency, its adoption is not recommended, even in association with the soil application of SAP. However, further assessment should consider the effect of the IRR_{50} + SAP strategy on net income.

The present study shows that the adoption of superabsorbent polymer is suitable for enhancing the drought stress tolerance of tomato crops, and a new irrigation water-saving strategy is further suggested with the IRR_{75} + SAP combination. Similar conclusions were reported by Satriani et al. [11], who showed that the yield of dry beans cultivated under 70% ET_c water restoration was not statistically different from 100% ET_c control if a SAP was applied to the soil. Patanè and Cosentino [31] demonstrated that restoring 100% of

ET_c up to the flowering stage, followed by the restoration of 50% of ET_c from the flowering to the harvest stage, did not significantly reduce the yield and improved the IWUE of processing tomatoes in southern Italy. Accordingly, the integration of SAPs in regulated deficit irrigation strategies needs to be an object of further investigation.

To our knowledge, this is the first study that shows that the application of SAP to the soil did not affect the main fruit quality parameters in processing tomatoes (Table 2), allowing farmers to maintain the high quality of their products commonly achieved with the common farmer strategy (IRR_{100}). However, neither irrigation treatment affected the quality of the fruits (Table 2), differently from what was reported in previous studies. Indeed, Patanè and Cosentino [31] and Patanè et al. [23] showed that reducing the water applied with irrigation in processing tomatoes led to an increase in the TSS and fruit firmness. Therefore, further experiments are recommended to confirm the absence of SAP effects on quality traits.

5. Conclusions

The present study clearly showed that SAP application to soil allowed for reducing the amount of irrigation water up to 25% of the crop requirements in processing tomato production in northern Italy and increased the IWUE by up to 37%. SAP allowed a high yield to be maintained because of the increase in fruit numbers produced by plants, but it is not suitable for reducing the percentage of sunburned fruits under severe water stress conditions. However, further studies are required to also confirm the present results in a strictly arid environment (e.g., in southern Italy, where the successful production of processing tomatoes is strongly limited by the water availability), and the absence of effect in qualitative traits. Economic assessments on the adoption of superabsorbent polymers are still lacking and may stimulate their adoption by farmers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae8080718/s1.

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